GEOMORPHOLOGICAL CONTROLS ON THE SEDIMENTATION PATTERNS OF, AND DISTRIBUTION OF ANTHROPOGENIC RADIONUCLIDES IN, COASTAL SALTMARSHES, SOUTH-WEST SCOTLAND

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VOLUME ONE

VOLUME TWO

DECLARATION

Except where specific reference is made to other sources, the work presented in this thesis is the original work of the author. It has not been submitted, in part or in whole, for any other degree.

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ABSTRACT

The saltmarshes within the Solway Firth are often regarded as a single unit, all experiencing similar physical conditions. This work demonstrates that they are different, each with a unique characteristic and quality. These qualities are identified and a new classification system for the Solway saltmarshes is proposed.

With reference to these differences, the study investigates variations evident in sedimentation patterns utilising a number of methods which operate over different timescales. These methods are successfully integrated to provide a historical analysis of the dynamic nature of the Solway saltmarshes. The results indicate that the Solway marshes undergo rapid change and that this change is related largely to hydroperiod and vegetational influences.

An integral part of this work is the utilisation of Sellafield derived contaminants as a tool to investigate sedimentation patterns. In addition to this, the distributions of the radionuclides are examined and interpreted with reference to the sedimentary status of the marshes under investigation.

Many authors consider accreting saltmarshes to be long term stores for radioactive contaminants but this study demonstrates that physical and chemical dispersion of some radionuclide species indicates that the saltmarsh store is ephemeral.

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1. RATIONALE

1.1 Introduction

Saltmarshes are regarded as being one of the most productive ecosystems in the world, due largely to their capacity to act as sinks for organic and fine-grained inorganic sediment (Long and Mason, 1983). They are found mostly on sheltered coasts and, as these are also favoured as industrial sites, saltmarshes are frequently affected by pollutants, such as oil, heavy metals and radionuclides (Valette-Silver, 1993). These pollutants are often local to the saltmarsh but may also be transported into estuaries from inland and marine sources (Adam, 1990). This capacity for trapping pollutants is viewed by many involved in waste management as a beneficial attribute of saltmarshes. Niering (1977) demonstrated that nitrate and phosphate levels from sewage effluent were reduced by 50-70% after being passed over tidal marshes. Giblin *et al.,* (1980) investigated the use of saltmarshes in sewage treatment systems and noted that they were extremely efficient at trapping Fe and Pb in a form unavailable to marsh biota. Saltmarshes also have the ability to use and transform some pollutants, particularly those derived from sewage, so curtailing the development of hazardous environmental conditions such as red tides (Perkins, 1977).

The sorptive capacity of saltmarshes cannot, however, overshadow the fact that pollutants within a saltmarsh may ultimately be reintroduced into the estuarine environment because of the ephemeral nature of saltmarsh systems. Saltmarshes may accrete or erode sediment depending on a number of local (e.g. tidal range, sediment supply) and regional (e.g. sea level rise) environmental factors. For example, metals bound in sediment or organic compounds resistant to chemical degradation can be reintroduced into surrounding waters by physical disruption of the marsh or biological activity within it (Luternauer, *et al.,* 1995). Oil which accumulates in the reducing sediments of the marsh can show remarkable persistence, contrary to the rapid breakdown experienced by petroleum released to the sea (Corredor, *et al.,* 1990) and may therefore remain a threat to wildlife utilising the marsh environment. Some species of radioactive nuclides may remain in the environment for greater timescales than the life of the marsh in which they might reside. These examples accentuate the need to understand saltmarsh systems as part of any pollution monitoring strategy. Indeed, the question of what happens to any waste material on becoming incorporated in a sediment is of great importance in relation to dumping (Perkins, 1977). The heavy use of coastal areas for industrial purposes, the increasing use of marine waters as waste depositories and the subsequent pollution impact on saltmarshes and the wildlife which inhabits them, have created a need to integrate pollution and geomorphological studies. Understanding the depositional environment of polluted sediment will facilitate the construction of comprehensive, cost effective strategies for monitoring pollutants. It also allows the future mobility and eventual fate of the pollutant to be accurately predicted.

That pollutants are subsumed into saltmarshes raises some fundamental questions. To what extent do saltmarsh processes and characteristics control the distribution of pollutants? How can these pollutants be effectively monitored? What is the long term fate of the pollutants? The general acceptance of saltmarshes as pollutant sinks has led to insufficient investigation into this important aspect of saltmarsh systems and these questions have been addressed in few saltmarsh studies. Allen and Rae (1986) used the existence of zinc and lead within saltmarshes to establish the impact of mining on the release of these metals into the environment. Allen (1987a) concluded that the grain size of sediment rather than geographical position had over-riding influence over the amount of pollutant coal dust in intertidal deposits. For the most part, pollution within saltmarshes is used as a tool for further investigations about saltmarsh processes rather than *vice versa*. (Delaune, *et al.,* 1978, Aston and Stanners, 1979, Stanners and Aston, 1981a, Allen, 1988, French *et al.,* 1994, O'Reilly Wiese *et al.,*1995).

Perhaps the most contentious of all pollution is that resulting from the nuclear industry. Unlike oil and most metals, people cannot see, smell or touch radiation and this instils a sense of suspicion into the general public: a suspicion intensified by accidents such as the Chernobyl disaster in 1986. The greatest input of artificial radioactivity into the marine environment around the coast of Britain is that discharged, under authorisation, from the Sellafield Nuclear Fuel Reprocessing Plant in Cumbria (henceforth Sellafield) (Hutchinson, 1994). This plant has been discharging low level radioactive waste since 1952 (Garland *et al.,* 1988). For three decades workers have noted elevated levels of radionuclides in intertidal areas in Cumbria (e.g. Hetherington and Jefferies, 1974, Aston and Stanners, 1981a, b, Aston *et al.,* 1981,), North Wales (Garland *et al.,* 1989) and south-west Scotland (e.g. Jones *et al.,* 1984, MacKenzie *et al.,*1987). Of these intertidal areas, saltmarshes are more enriched than tidal silt or mud banks (Aston and Stanners, 1981). However, this observation must be viewed carefully given that estuarine sediments are more variable than true marine sediments (Balls *et al.,* 1997). Aston and Stanners (1982a) established that there were "significant variations" in the distribution of fission products in surface sediments of the Ravenglass estuary. As a consequence they warned that "care must be taken in the use of estuarine sediment sampling to evaluate the external dose to the public frequenting such locations since the small scale areal variations in radionuclide activities for surface sediments are significant". The need for investigation of the sedimentary processes contributing to the dispersion and deposition of radionuclides was reiterated by MacKenzie *et al.,* (1987). Allan (1993) stressed that only by understanding the geomorphology of saltmarshes would the distribution of radionuclides within the marshes be understood and accurate inventories quantified.

The Solway Firth, south-west Scotland, contains the largest expanse of saltmarsh in Scotland, with one third of all Scottish marshes found within its sheltered bays and estuaries. The marshes are internationally important but despite this there has been a paucity of studies (Morss, 1925-26, Marshall, 1960-61; 62; Gimingham, 1964; Bridson, 1979; Nelson, 1979). The marshes of the Solway are contaminated with radionuclides derived from Sellafield (MacKenzie and Scott, 1982, Jones *et al.* 1984). While a number of studies have identified general patterns in the distribution of the radionuclides (MacKenzie and Scott, 1982, Allan *et al.,* 1991, McDonald, *et al.* 1992, MacKenzie *et al.,* 1994), none of the data produced to date have been viewed in a geomorphological context, i.e. they have not considered the spatial and temporal variability inherent in saltmarsh erosional and depositional systems. The saltmarshes along the Solway vary in terms of their development and character (Harvey and Allan, 1998), offering a unique opportunity to investigate not only saltmarsh variability within a small geographic area, but also the impact that this variability has on radionuclide distributions.

1.2 Aim

The encompassing theme of this work is to determine the role which geomorphology plays in the distribution of Sellafield derived radionuclides in the Solway Firth saltmarshes. An important component of this investigation will involve determination of existing sedimentation patterns, consequently allowing the radionuclide distribution and inventories to be ascertained. In order to realise this theme, the Solway marshes must initially be categorised and characterised before the pattern of radionuclides can be adequately explained. The specific aims are outlined in Chapter two following a discussion of the relevant literature in this study.

1.3 Study Parameters

Any investigation involving monitoring of the environment must define the spatial and temporal scales confining the study. The variability of scale within geomorphological studies can be described as "the fundamental skeleton" (Kennedy, 1977, p. 156) of geomorphology. The scale of any study will not only mould the interpretation of spatial and temporal patterns but will influence the initial project design and specifications, therefore a brief consideration of the 'scale problem' is appropriate.

This study aims to determine the extent to which geomorphological patterns and processes affect the distribution of radionuclide contamination in saltmarshes. Understanding a spatial or temporal pattern is determined by the identification of some controlling process, or processes, but different processes can become significant at different scales (Harvey, 1968). French *et al.* (1995a) demonstrate on Norfolk marshes that different scales of inquiry result in different controlling factors being identified. In Norfolk, saltmarsh accretion at a broad scale is controlled by the topography of the marsh, whereas more detailed analysis showed that on a small scale, the main control on accretion was the distance from the creek system. Another example of this is given by Phillips (1986) considering shoreline erosion: "in determining the overall pattern of erosion, which is more important: large scale differences in exposure caused by geographic situation or local differences in exposure caused by landscape irregularity?" He argued that in order to establish the factors controlling erosion, the critical spatial scale of variation must be identified. The scale at which most variation in a landform occurs needs to be identified before assessing the factors which control that variation, within the established scale.

In a study of the erosion of the shores of Lake Erie, Canada, attempts to establish an average rate of erosion was a "useless exercise" because the process of shore retreat is discontinuous, occurring irregularly in space and time. It was concluded that "average rates of retreat are meaningless" (Packer, 1971). It is problematic to take a series of measurements over a large spatial scâle and simply average them to gain a picture of the whole.

From these examples two distinct problems emerge:

1) in geomorphic situations it is not always valid to use the averages of sampled data to determine characteristics of a whole population, but at the same time, it is usually impossible to investigate the whole population due to logistical constraints, and;

2) the results of research undertaken at one scale are not necessarily applicable at another scale.

The first of these problems relates specifically to "scale coverage" (Hagget, 1970), and with it brings the central issue of sampling (Thorn, 1988). We cannot assume that the pattern observed in a sample holds for its population, the so-called 'universal fallacy' (Alker, 1969). In geomorphology, the role of probability or random sampling is limited. Random, unbiased samples are imperative in inferential statistics but often a geomorphologist will wish to investigate some particular landform or a set of features within a landform. Random sampling requires a degree of homogeneity in a study area rarely found in the natural landscape. Therefore, sampling in geomorphology is purposive (Harvey, 1969), with the researcher choosing representative sample areas based on knowledge. The sample may well only be n=1, with the researcher intentionally choosing some unique aspect of the landscape. Indeed, some feel that the apparent randomness of the landscape can only be understood by investigating these unique situations (Gould, 1970).

The consequence of this purposive regime is often a stratified sample set, with each sample being chosen to represent a particular aspect of the landform in question. By stratifying a complex landscape we can ensure, or at least hope for, a representative sample set (Wood, 1955). This strategy has been used to great effect by those in the field of hydrology where it can be supposed that the drainage basin can be stratified into sub-units. Each sub-unit will differ according to factors such as cover type, soil depth, position on the slope and position in the basin. By choosing one example from each group of sub-sets, a more precise model of the basin as a whole can be generated. Identifying sub-units in other aspects of the landscape can be problematic but despite this, stratified sampling has a role to play as a method of ensuring that the patterns observed in a set of samples can be used to determine the character of the whole.

The second problem is that of 'scale linkage' and stems from the practical constraints which force a researcher to investigate on a small scale when interested in much larger areas. The crux of the problem lies in the fact that different factors will dominate process - response relationships at different spatial scales. For example, at a small, micro-scale, the coast will be shaped by tidal action but at a world-wide, macro-scale, the coast will alter in response to changes in the climate. A widely used approach to solving this is to smooth locally generated data, of similar nature, so that broad patterns emerge. Although this results in a loss of resolution, it does mean that a general pattern for the whole sample set can be determined, under appropriate constraints of time and effort.

Throughout this work the two problems of scale coverage and scale linkage will be alluded to. The variability of marshes within the Solway affords a unique opportunity to test methods of ensuring a comprehensive scale coverage, both spatially and temporally.

1.4 Thesis structure

This chapter has laid a broad foundation for the study and this is developed in a review of relevant literature regarding saltmarshes and their contamination by anthropogenic radionuclides in Chapter two. In response to gaps identified in the current literature, the specific aims of the study are further detailed. Chapter three describes the study area and investigates the current status of the Solway marshes. This information is then used in Chapter four in order to validate the sampling strategies adopted as a consequence of the constraints outlined above. The lab and field methods used are also described and discussed in this chapter. Chapter five summarises the results gained from the geomorphological and radiological investigations. Chapters six and seven discuss the relationships found with reference to the aims outlined in Chapter two. Chapter eight forms the conclusion.

2 SALTMARSHES: DEVELOPMENT PROCESSES AND CONTAMINATION BY ANTHROPOGENIC RADIONUCLIDES

SALTMARSH DEVELOPMENT PROCESSES

2.1 Definition of saltmarshes

Saltmarshes are complex environments, studied by a range of scientific disciplines. Consequently, myriad definitions are available, stressing one or other physical attribute: ecologists emphasise species diversity and associations, whereas geomorphologists stress water/sediment interactions. It is therefore worth spending some time developing a coherent definition of saltmarshes for use in this work.

Saltmarshes can be simply defined as "well-vegetated saline intertidal flats" (Frey and Basan, 1978, 1985). While this generic definition implies colonisation of the intertidal area by halophytic species, it gives little indication of the marsh location within the intertidal zone, the substrate composition or the degree of salinity. Frey and Basan (1978, 1985) categorically exclude from their definition unvegetated mud and sand flats, subtidal vegetated substrates and low-intertidal to subtidal sediments underlying the marsh sediments. To some extent this belies the inter-dependent nature of marshes and sand/mud flats (Pethick, 1992, 1996). A more complete definition by Long and Mason (1983) synthesises the physical and biological attributes of a saltmarsh as "areas of alluvial or peat deposits, colonised by herbaceous and small shrubby terrestrial vascular plants, almost permanently wet and frequently inundated with saline waters". This definition gives a clearer impression of marsh vegetation and substrate and its inundation by saline waters.

Distinctions have been made by some authors between coastal marshes and those within estuarine systems. Adam (1990) suggests that coastal saltmarshes are a subset of the wider category tidal marsh, with there being "a continuum between coastal saltmarsh and marshlands in the upper estuary subject to tidal but non-saline flooding". Given that *salt*marshes are geographically more extensive than upper estuarine marshes and the important physiological differences between these marsh types, this grouping appears inappropriate. A distinction should be made between saline and non-saline tidal marshes: these marshes are different and should be treated as such. Luternauer *et al.* (1995) suggest that estuarine marshes differ from coastal marshes because the former can be inundated with both saline and fresh waters and also receive sediment from both sources. Although tidal waters entering an estuary are diluted by riverine water there is still, however, a substantial saline input which the marsh vegetation must be able to withstand. In this important respect therefore, coastal and estuarine marshes are similar.

Further definitions are offered by Chapman (1974): "areas of land bordering on the sea, more or less covered with vegetation, and subject to periodic inundation by the tide"; and Allen and Pye (1992): "environments high in the intertidal zone where generally muddy substrates support varied and normally dense stands of halophytic plants". It is rare for a saltmarsh definition to be both concise and all encompassing. The latter definition is, however, a good one, indicating the location of saltmarshes within the coastal zone, the dominance of, and variety within, the halophytic vegetation and the nature of substrate material. In addition to this, an indication of global location is required because this definition could include tropical mangroves. In general mangroves replace saltmarshes on coasts where the mean temperatures of the coldest and warmest months exceed 10°C and 15.5°C respectively (Long and Mason, 1983). In subtropical and warm temperate areas, saltmarshes and mangroves can co-exist. Mangroves can, therefore, be considered a tropical version of saltmarshes (Steers, 1977). Consequently, the definition adopted here is "saltmarshes exist in temperate environments, high in the intertidal zone where fine-grained substrates support varied and normally dense stands of halophytic plants".

2.2 Saltmarsh development

2.2.1 Introduction to saltmarsh development

The above definition provides a basis uopn which to discuss the geomorphological development of saltmarshes. Numerous authors have published comprehensive accounts of saltmarsh systems (e.g. Chapman, 1974, 1976, 1977; Adam, 1980; Long and Mason, 1983; Allen and Pye, 1992). Briefly, saltmarshes develop in sheltered areas as a result of the attenuation of wave and tidal energy. Vertical accretion of tidal flats to a level above that of the mean high water neap facilitates colonisation by halophytic plants, which further encourages sedimentation of both organic and inorganic material. Accretion continues through successive tidal inundations until the elevation of the marsh is such that tidal submergence no longer contributes sediment. A number of factors, partly implied by the definition given above, can be identified as controls on saltmarsh accretion, including: tidal regime; wave energy; relative sea level; sediment supply; marsh topography and elevation; and vegetation. The relative importance of these factors varies from place to place and from marsh to marsh. Before these factors are discussed in detail, the location of marshes should be considered, since the physiographic setting of a marsh will characterise which of the above factors will dominate marsh development processes. For example, marshes on an open coast will be subject to greater wave activity than those contained within a sheltered bay; marshes fringing large estuaries may have a greater supply of fine sediment (from coastal and terrestrial sources) compared to those on an open coast.

2.2.2 Influence of physiographic location on saltmarsh development

Marshes will only develop in locales where wave and tidal energy is attenuated by the shelter of a physical feature, such as a spit, or an extensive inter-tidal plain. It is only in such low energy environments that the competence of the sediment-bearing water is reduced sufficiently to allow deposition of the sediment necessary to increase mudflat elevation and initiate marsh development. A variety of physiographic features, listed in Box 2.1, have been identified as being suitable for the development of saltmarshes.

Within any geographic area, a number of physiographic units may exist, creating a complex network of marsh systems. Long and Mason (1983) recognise that marsh types are not mutually exclusive and that intermediate types will exist. Marshall (1962) suggests that the classification of marshes on the basis of physiographic features is artificial, because marsh development often results from a combination of conditions.

Physiographic type	Author(s)	Description	Examples
Estuarine; enclosed bays	Chapman, 1974; Beeftink, 1977; Allen and Pye, 1992	Marshes found fringing estuaries and sheltered bays located on a gentle coastal plain with a shallow sea bed. River flow should not be excessive but may have strong tidal currents. Salinities fluctuate largely. Probably most abundant type.	Most rivers have some marsh, e.g. Chesapeake Bay; River Severn; Solway Firth, SW Scotland.
Barrier island marshes; Wadden type; offshore bar type; back-barrier; barrier connected	Chapman, 1974; Beeftink, 1977; Dijkema, 1987; Allen and Pye, 1992	Marsh development occurs behind a chain of offshore barrier islands lying parallel to the coastline	Dutch-German-Danish Wadden area; Scolt Head Island, Norfolk; Georgia, USA.
Lagoonal marshes; spit marshes	Chapman, 1974; Beeftink, 1977; Long and Mason, 1983	The development of sand or shingle spits parallel to the coastline encloses a body of tidal water, leaving only a narrow connection with the sea. Marsh development is encouraged by reduced wave energy and tidal amplitude.	Poole Harbour; Venice and Triste lagoons; Blackeney Point, Norfolk; Nelson Harbour, New Zealand.
Open coast marshes	Chapman, 1974; Allen and Pye, 1992	Marshes found on open coasts where the sea is very shallow, such that large waves will not form, or where the extent of open water is not great.	Malmo, Sweden; the Wash;
Beach plain marshes; embayment marshes; foreland marsh	Beeftink, 1977; Dijkema, 1987; Allen and Pye, 1992	These marshes either protected by sand or shingle bars (sometimes surmounted by dunes), which are covered during high tides, or are unprotected.	Dengie Peninsula; Florida Panhandle
Bog type; peat type	Beeftink, 1977	Formed by a gradual subsidence of the coastline mainly by the deposition of autochthonous plant material. Usually occur in areas of heavy rainfall.	south west Ireland; New England coast; southern Baltic
Fjord-head or loch type; rocky shore types (including ria-bay types)	Gimingham, 1964; Dijkema, 1987; Allen and Pye, 1992	Located at the head of rocky or steep sided, coastal inlets. They are usually very small. Only 4% of European marshes are of this type.	north west Scotland; Scandinavian countries; Brittany; north west Spain
Polderland type; semi-natural marshes	Beeftink, 1977; Long and Mason, 1983	Marshes which have been significantly altered by human activity, e.g. reclamation.	south west Netherlands, Fens, east Anglia
Artificial marshes	Long and Mason, 1983	Saltmarsh created by human intervention, e.g. planting stabilising vegetation in otherwise mobile sand and mud deposits.	various locations around world

Box 2.1 Marsh types based on physiographic location

For example, marshes along the north Norfolk coast have formed in the lee of shingle barriers producing both back barrier and spit marsh systems. Large estuaries, such as the Solway Firth (Marshall, 1962) and Milford Haven (Cleddau estuary) (Dalby, 1970), and bays, such as Morecambe Bay (Gray, 1972), can be considered as single physiographic units, but they comprise a number of smaller estuaries, inlets and other physiographic features, all conducive to marsh growth of varying types.

The form of sedimentary coastal features (including saltmarshes) is determined principally by tidal range and wave energy (Beeftink, 1977). For example, the occurrence of spits in the English and Welsh coasts coincides with areas experiencing tides of less than 3 m (Pethick, 1984). The plan form of estuaries is shaped by tidal range: meso-tidal estuaries are short and wide while macrotidal estuaries are long and funnel-shaped (Hansom, 1988; Pethick, 1996).

Davies (1977) suggests that saltmarsh development is generally inhibited on coasts with low, or no, tides because in these environments, the tidal flat is constructed by irregular wind-induced waves resulting in high salinities and little plant colonisation. There are, however, exceptions to this apparent tidal control. Large saltmarsh systems are found in microtidal areas, such as Louisiana and the Mississippi delta because, as will be discussed more extensively later (section 2.2.4), sedimentation of these marshes is via storm activity (e.g. Stumpf, 1983) or organic deposition (e.g. Craft *et al.*, 1993) rather than tidal inundation. Saltmarshes are also found in micro-tidal systems where a physiographic feature shelters saltmarsh development, for example behind spits.

The influence of physiographic setting on saltmarsh development has been relatively neglected in saltmarsh studies. Numerous studies make reference to various marshes in geographically distinct areas but few have compared different marsh systems in close geographic proximity. Wood *et al.* (1989) noted that variability in the sedimentation rate between back-barrier, fluvial and bluff-toe marshes in Maine was related to the type and supply of sediment. Pethick (1981) used 14 different marshes on the North Norfolk coast to determine the relationship between the age and elevation of marshes. Difficulties arise, however, in comparing different marshes in different settings because each marsh type is geomorphologically distinct, with characteristic sedimentary processes (Stevenson *et al.,* 1988). As noted above, variations in marsh type are governed to a large, but not exclusive, extent by tidal conditions, which in turn influence all other aspects of marsh development. The problem of studying the impact of physiographic location would therefore be mitigated to an extent where different marsh types are located within a single area (Stevenson *et al.*, 1988), thereby experiencing similar tidal conditions.

2.2.3 Sediment deposition on saltmarsh surfaces

Suspended sediment, comprising largely silt and clay sized particles and exceptionally sand particles, is carried onto the tidal flat or marsh by flood tides, often via tidal creeks. The provenance of this sediment varies. Rivers, off-shore or inner continental shelves, barrier washover, erosion of outcrops of older sediment, recycling of marsh deposits, wind blown sediment, organic aggregates and in situ biogenic sediment (Frey and Basan, 1978, Smith and Frey, 1985) have all been identified as sources of sedimentary material.

The deposition of sediment is controlled by the size of the particles and water velocity. As high tide is reached and the floodwaters overbank the marsh surface, the velocity of the flood tide reduces below a critical level, initiating the settling of particles contained in the flood tide. The critical velocity level is described by Stoke's Law, shown in Box 2.2. Reduction in water velocity occurs rapidly as the floodwater overbanks and this in turn causes the rapid deposition of sediment. French and Spencer (1993) determined that 95% of deposition on Norfolk marshes results from direct settling within a short distance from the source creek.

The movement and deposition of sediment on tidal flats, and saltmarshes, is often viewed as the function of two factors, described by Postma (1967) as settling lag and scour lag. Settling lag describes the process whereby particles are not dropped vertically below the place where settling begins, but are carried inland with the continuing flood current before they finally settle. The spatial pattern of deposition is not uniform and is governed by progressive particle settling along the pathway of water movement (French *et al.,* 1995b).

The terminal velocity V of a sphere, radius, r, and density, σ, falling in a fluid, density ρ, under the influence of gravity, is given by Stokes' Law from:

$$V = \frac{2 g r^2}{9\eta} (\sigma - \rho)$$

where g is the acceleration due to gravity and η is the coefficient of viscosity.

(Goudie, 1994)

Box 2.2 Stokes' Law

Scour lag occurs because of asymmetry between the velocity required to entrain a sediment particle and that at which the particle is dropped. Entrainment velocities are higher because of the shear resistance between the marsh surface and the particle. Particles of medium sand size can be moved at the lowest velocities, but higher velocities are required both for larger particles, because of their mass, and for smaller clay particles, because of their cohesive nature (Summerfield, 1991). The relationship between the entrainment and deposition of sediment can be illustrated by the Hjulström Curve, shown in Figure 2.1.

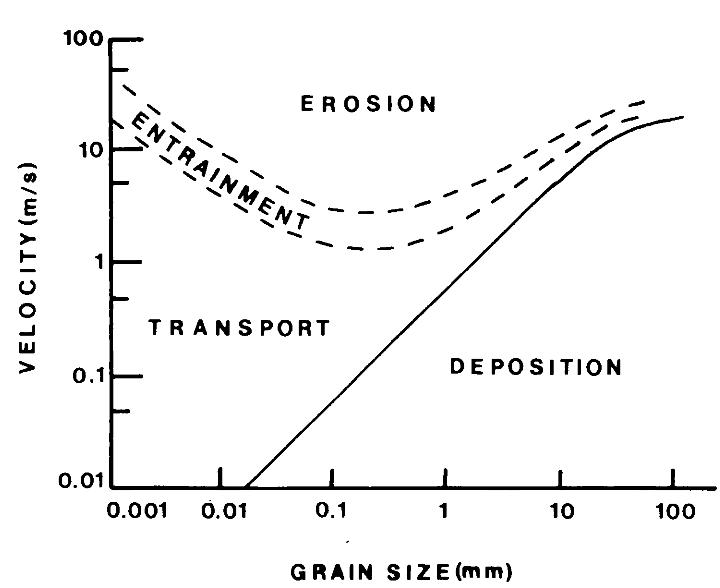

Figure 2.1 Hjulström Curve (from Knighton, 1998)

If, at any one point, the flood and ebb tides have the same velocity, particles deposited inland as a result of settling lag, will not be re-entrained by the ebb tide. This situation is enhanced by the asymmetric nature of tides, with flood tide currents being generally stronger than ebb tide currents (Pye and French, 1993). The combination of settling and scour lag therefore leads to a preferential movement of sediment up estuary and on to the marsh surface (Hansom, 1988). The pattern of sediment size distributions within the marsh also confirms settling and lag scour with the outer marsh and creeks banks comprising coarser sediment than the inner marsh (Evans, 1965; Pye, 1995): settling of fine sediment will only happen where the velocity is low (see Figure 2.1).

Leonard *et al.* (1995a) suggest that once suspended sediment is deposited on the marsh surface, neither flood nor ebb overland flow is capable of resuspending the sediment. The resuspension of sediment from the marsh surface may, however, depend on how quickly the marsh surface is re-inundated. Surfaces able to consolidate sediment through drying may not experience any resuspension of sediment (Hutchinson *et al.,* 1995), whereas areas of the marsh remaining waterlogged between inundations are susceptible to resuspension (Mehta *et al.*, 1982; Reed, 1988; Reed and Cahoon, 1992). This preferential movement of material onto the marsh surface is also described by Wolff *et al.,* (1979) for particulate organic material. It should be noted that seaward transport can also occur as a result of more dominant ebb tides, such as occurs in the marsh systems of west-central Florida (Leonard *et al.,* 1995b).

In addition to the processes of settling and scour lag, the duration of slack water immediately after high tide also determines the amount of sediment which can be settled, with more prolonged flooding leading to increased sediment accumulation (Letzsch and Frey, 1980; Reed and Cahoon, 1992; Cahoon and Reed, 1995). It might appear logical to presume that a shallow depth of slack water, say during neap tides, would allow sediment to settle more quickly. Wolanski *et al.,* (1992), however, measured more sediment settling during slack tides which were both long in duration and in deep water, because during these conditions the water has time to become quiescent, therefore encouraging particle deposition. In periods of short, shallow slacks, the water remains turbulent, making it more difficult for particles to settle. The depth of tidal water was also recognised by Dankers *et al.* (1984), working in the Ems-Dollard estuary in Holland, as a controlling factor in the amount of sediment deposition. They calculated that approximately 40% of particulate matter transported by the flood current remained on the marsh during normal tides with the quantity being greater during storm conditions.

The net transport of suspended organic material (as opposed to inorganic sediment) depends on the relative concentration of organic material on the marsh and the flooding waters (Wolff, *et al.,* 1979). Marshes with a high organic productivity compared to the flooding water will export, rather than import, organic material (Odum and de la Cruz, 1967) to the sub-tidal system.

The processes described above can account for some of the sedimentation trends found on the marsh, and have been summarised by Letzsch and Frey (1980), as shown in Box 2.3. In addition to these factors, sedimentation rates are generally higher at the edge of creeks than in the middle of the marsh (e.g. Redfield, 1972; Pizzuto, 1987; French and Spencer, 1993) because the velocity of tidal waters is reduced as they overbank.

1. net deposition rates are generally low;
2. deposition rates increase with tidal range;
3. deposition in low marsh habitats exceeds that of high marsh habitats;
4. rates of deposition or erosion vary seasonally and annually;
5. sediment accumulations may be enhanced by subsidence of the substrate or eustatic rises in sea level;
6. rates of deposition decrease with increased marsh maturity or with increased marsh stability.

Box 2.3 Trends of saltmarsh sedimentation (Letzsch and Frey, 1980)

2.2.4 Spatial aspects of sedimentation

From the above discussion it would appear that the settling of sediment from tidal water, modified by settling and scour lag processes and the duration and depth of the slackwater period, is an essential part of marsh accretionary processes. It is however argued that settlement from tidal suspension alone is inadequate to explain the thick accumulations of mud which can exist on saltmarshes (Frey and Basan, 1978). Stumpf (1983) suggests that turbulence and a short slack water period prevent the deposition of fine sediment and that additional methods of sediment deposition are required. Nor can settling alone supply the coarse sand/silt sized particles of which many marshes are composed (Stumpf, 1983). Letzsch and Frey (1980) noted that areas of ponded water, rather than inducing sediment settling, promoted scour and resuspension of clay material because of wind induced waves. In addition, the sedimentation of some marshes has been shown not to be a consequence of daily tidal inundation (Cahoon *et al.,* 1996).

To address these issues and apparent contradictions, the general pattern of accretion on saltmarshes should be considered. The transition from mud/sand flat to saltmarsh occurs as the flat reaches the level of the mean high water neap (MHWN) and vegetation begins to colonise. The highest rates of sedimentation occur at the seaward end of the marsh, reducing with height and marsh maturity (e.g. Letzsch and Frey, 1980; Pethick, 1981; Gray, 1992). Indeed, Stevenson *et al.* (1986) established that a linear relationship between tidal range and sedimentation rate exists. Accretion of the marsh may continue until only extreme tidal conditions are capable of flooding the surface, supplying it with sediment. A relationship therefore exists between the rate of sedimentation, the frequency of tidal inundation and the elevation of the marsh, described by French and Spencer (1993) as a "powerful form-process feedback". As the marsh surface rises, the hydroperiod reduces, limiting the supply of sediment (Carter, 1988), making elevation the principal control on long term sedimentation rates (French, 1993).

Whilst this relationship between marsh elevation and sedimentation rates is intuitively appealing, it is not the case on all marshes, particularly those where tidal inundation is not the dominant accretionary process. Sedimentation on the microtidal marshes of Louisiana is storm driven and affects all elevations (Reed and Cahoon, 1992), rendering the elevation - sedimentation feedback argument invalid. In addition to this, Reed and Cahoon (1992) note that sites subject to high frequency and long duration flooding are likely to suffer plant deterioration, ultimately resulting in lowering of the marsh surface. Cahoon and Reed (1995) argue that more prolonged, deeper flooding will only increase sedimentation if there is vigorous plant growth. Craft *et al.,* (1993) measured higher accretion rates in irregularly flooded micro-tidal marshes due to reduced tidal flushing of organic matter which, in this case, was the main accretionary material. In this situation, plant growth, rather than elevation, controlled organic sedimentation.

Theoretically, a marsh may attain a maximum height equalling the level of the highest astronomical tide. Kestner (1975) noted that accretion reaches an asymptote some distance below the highest tidal level. Pethick (1981) concluded that the asymptote coincided with the level of the modal tide rather than the highest tide because beyond the modal tide limit, the frequency of tidal inundation falls rapidly, resulting in no further accretion. French and Spencer (1993) and Hayden *et al.* (1995) suggest that marsh elevation increases through sedimentation, may be offset by regional subsidence and that enhanced sedimentation during high spring tides and storms is important for maintaining the highest parts of the marsh. This offers some explanation to the criticisms regarding the size of sediment required to build the marsh surface. The higher competence of storm induced inundation will allow coarser sediment greater access to the back of the marsh than during 'normal' astronomic tidal flooding. It should also be noted that the texture of marshes also depends on the type of sediment available for marsh accretion. Some Scottish marshes, for example Morrich More, are composed of silt/sand because of a regional lack of fine silts and clays (Hansom and Leafe, 1990).

The maximum thickness of marsh sediment which accumulates over time will vary greatly with tidal range (Steers, 1977), especially in areas with a high tidal range and varying sea level. The overall marsh thickness will be lower than the sum of annual sediment accretion because of settling processes, in particular, the oxidation of organic matter and compression from the weight of overlying sediment (Ranwell, 1964a). The amount of compaction likely to occur in marshes is directly related to the organic content of the sediment and inversely related to the amount of sand (Harrison and Bloom, 1977). Flooding of the marsh may occur due to eustatic sea level changes and subsidence due to isostatic adjustments.

Sediment accumulation on marshes as a result of storm activity is now recognised as an important source of inorganic sediment on many microtidal* marshes (e.g. Stumpf, 1983, Craft *et al.*, 1993, Reed 1989; Reed and Cahoon, 1992). On meso* - and macro*-tidal marshes, storm induced accretion is considered important, especially for long term sedimentation on the highest marsh surfaces (French and Spencer, 1993), but not crucial (Leonard *et al.*, 1995b). In macro-tidal systems, the incidence of spring tides is extremely important with regard to increased sedimentation. Not only do spring tides increase the duration and depth of tidal flooding but they can increase the amount of sediment available for deposition. Postma (1967) notes that the strong currents during spring tides will bring more material into suspension than neap tide currents. Studies in the Forth estuary (Lindsay *et al.*, 1996) showed the spring/neap cycle dominated control of the transport of suspended material with the "largest spring tides exerting a disproportionate influence on sediment transport". Ranwell (1964a) determined that 75% of the total annual accretion occurred from August to October and attributed this to the incidence of increasingly large tides prior to the autumnal equinox. Storm activity can also increase the amount of sediment available for deposition, with additional sediment coming from scouring of creek bottoms (Baumann, *et al.*, 1984, Reed, 1988), increased river flow (Cahoon *et al.*, 1996), erosion of the marsh edge and fronting tidal flat (Reed, 1988) or resuspension of sediment previously removed from the marsh surface (Leonard, *et al.*, 1995b).

Associated with marsh accretion is the creation of a network of creeks which channel flood and ebb tides into and out of the marsh and are considered instrumental in the transport of sediment onto the marsh during spring tides. Many creeks display a leveed bank, created as sediment is deposited when floodwaters overbank. Sedimentation rates generally decline away from creek edges and towards the back of the marsh (e.g. Letzsch and Frey, 1980; Oenema and DeLaune, 1988; Stoddart *et al.*, 1989). French (1993) argues that the rate of sedimentation is controlled by proximity to creeks on a

* Microtidal marshes are those where the tidal range is less than 2 m. Mesotidal marshes have a tidal range of between 2 m and 4 m. Macrotidal marshes have a tidal range in excess of 4 m (Pethick, 1984).

short time scale and elevation on a broader timescale. In addition, the grain size of sediment also declines away from the marsh and creek edges (Letzsch and Frey, 1980; Stumpf, 1983; Allen, 1992b). The importance of creeks in sediment supply is challenged by Pethick (1984) who argues that, while tidal flows which occur below the level of the marsh are carried by tidal creeks, inundation of the marsh surface occurs because of overflow of the seaward edge of the marsh rather than via the creek system. French and Spencer (1993) attribute up to 40% of flood-tidal exchange during highest spring tides to overflow of the seaward edge, emphasising its importance.

The inception and development of saltmarsh creeks is also the subject of debate (see Pethick, 1992; Dankers *et al.,* 1984; Carter, 1988). The general pattern of saltmarsh creeks is determined by deeper random irregularities at the earliest stages of marsh development, and as the elevation of the marsh increases, the creeks become more entrenched, developing a typically steep sided or stepped morphology. The complexity of creek networks and their cross-sectional pattern is fashioned by the tidal range and sediment type. Marshes within a high tidal range with sandy sediment will have a less complex creek pattern than marshes in areas with a moderate tidal range and muddy sediment (Adam, 1990). Muddy marsh creeks are generally steep-sided, because mud is more cohesive, whereas sandy marshes often show a two tier channel with fallen blocks of sandy mud held together with vegetation on the upper tier (Steers, 1977).

The spatial variability in sedimentation rates in a marsh, especially early in its development, creates patches or wide hollows of unvegetated ground, known as pans. These are not considered to influence marsh sedimentation directly, although the sedimentation rates in pans can be high due to tidal waters becoming trapped and allowing suspended sediment time to settle (Letzsch and Frey, 1980; Moreira, 1992). A number of possible origins have been presented in the literature and it is likely that on any one marsh, pans develop through a combination of processes.

The origins of pans were first presented by Yapp *et al.* (1917) and, although little evidence was presented to substantiate the conclusions drawn, these original ideas are now the accepted theory for pan formation (Pethick, 1974). Pans can be distinguished as being either primary or secondary. Primary pans are formed during marsh initiation due to the uneven nature of sediment deposition and plant colonisation. Higher parts of the tidal flat will become vegetated before low areas. These bare patches, being progressively lower than the surrounding vegetated marsh, collect water which, during warm conditions, evaporates leaving a saline crust. Subsequent re-wetting produces a hypersaline solution which prevents plant colonisation. These pans, through time, acquire a circular shape as a consequence of small eddies, wavelets and erosion produced after tidal flooding (Chapman, 1974).

Pans are also formed as a result of tidal litter being deposited on higher marsh areas (Ranwell, 1964a, Pethick, 1974). Litter deposited on the high marsh during spring tides will remain for some time, creating a patch of bare ground. Finally, 'rotten spot' pans are produced as a result of vegetation die-off as a result of persistent snow cover or waterlogging (Packham and Willis, 1997).

Secondary pans, often linear in form, are produced when creeks are blocked by bank collapse or by the colonisation of vegetation in front of an eroding marsh edge (Chapman, 1976). These pans can also form as a result of the abandonment or capture of creeks due to changes in the dynamics of the creek system. Such a change could be instigated by changing sea levels or the progressive increase in marsh height due to accretion. In this latter case, as the marsh increases in height, the creeks become deeper, accommodating a greater volume of tidal water. Consequently, fewer creeks are required resulting in some becoming obsolete, ultimately forming linear pans (Pethick, 1984).

2.2.5 Influence of vegetation on sedimentation

Despite the obvious influence of settling on the deposition of inorganic sediment, many authors argue that sediment deposition is facilitated by marsh vegetation (Frey and Basan, 1978) and in some cases that this has more importance in sediment deposition than direct settling (Stumpf, 1983).

The establishment of vegetation is determined largely by hydroperiod, in particular the frequency of submergence and emergence of the tidal flats, and by the amount of light reaching plants as they are submerged (Ranwell, 1972). It is generally accepted that colonisation of tidal flats by saltmarsh species occurs at the height of the Mean High

Water Neap (e.g. Long and Mason, 1983), preceded in some instances by the development of an algal mat. Common pioneering species in Britain are *Salicornia* spp., *Puccinellia maritima* and *Spartina* spp., all of which are able to withstand prolonged periods of tidal submergence and, during low neap tides, drought. Many species found on saltmarshes are not specifically halophytic (species which complete their life cycle in saline environments*), but are salt-tolerant (Carter, 1988).

Zedler and Beare (1986) argue that the germination and survival of saltmarsh species seedlings relies on a two to three week 'gap' of reduced salinity initiated by winter rainfall or increased streamflows. Pioneering species also require a sheltered location and a firm substrate to provide a good roothold, with aerated conditions (Chapman, 1974). Wiegert *et al.* (1981) suggest that a sheltered location is required, not so much to provide the necessary conditions for sediment accretion, but to prevent mechanical damage of seedlings by wave activity. Resistance to mechanical damage is also thought to assist in preventing damage from high salinities especially in those plants with succulent leaves, such as *Salicornia* (Ranwell, 1972). The colonisation of one species as opposed to another can also be conditional on sediment texture. Plant growth and colonisation can be retarded in nutrient poor, unstable sandy conditions (Randerson, 1979). Studies in Holland determined that *Spartina* dominated the colonisation of clayey saltmarshes whilst in the silty and sandy saltmarshes *Puccinellia* successfully competed against monospecific *Spartina* swards (Scholten and Rozema, 1990), a pattern borne out by the dominance of *Puccinellia* in sandy Scottish marshes (Gimingham, 1964).

Once colonisation of a tidal flat begins, sediment deposition is enhanced by vegetation in a number of ways. Vegetation, through friction, reduces the velocity of the incoming tide and waves, causing a reduction in transportation competence and subsequent deposition of sediment. Frey and Basan (1978) demonstrated a reduction in wave height and energy by 71% and 92% respectively, as a result of vegetation. Investigations on

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* The term 'halophyte' has a number of different definitions which are reviewed by Adam (1990). The definition used here is the most all-embracing version postulated by Flowers (1975).

Spartina marshes demonstrated that the grain size of deposited sediment increases away from the location of *Spartina* swards indicating a vegetation induced reduction in tidal velocity (Christiansen and Miller, 1983). The incidence of vegetation may ultimately induce the stilling of incoming water in order to allow suspended sediment to settle (Christiansen and Miller, 1983; Stevenson *et al.,* 1988). The roughness of the marsh surface as a consequence of vegetation will also facilitate sediment deposition around the base of individual swards and on leaves and stems or, as illustrated in the Tay estuary, in the hollow stems of broken plants (Alizai and McManus, 1980). *Spartina* stems are capable of trapping up to 50% of the suspended sediment within a spring tide (Stumpf, 1983). Experiments conducted in the Solway Firth demonstrated that up to 90% of the total sediment deposited was onto vegetation (Bieniowski, 1999).

An important effect of plants may also be to protect the marsh surface from reworking and erosion by binding the sediments with decayed organic matter (Evans, 1965; Ingram *et al.,* 1980), encouraging further plant growth, although this has not been tested in a quantitative manner (Allen, 1992b). In addition, dying vegetation can act as an *in situ* source of sediment. This source of sedimentation is especially important in micro-tidal marshes (Stevenson, *et al.,* 1986). Older or higher marshes, experiencing irregular flooding, may also rely on autochthonous sedimentation for their growth (Moreira, 1992; Allen, 1992a; Craft *et al.,* 1993).

Continuing sedimentation increases the level of the marsh, and pioneer species are superseded by species suited to less frequent inundation by saline waters, thereby creating a zoned pattern of colonisation. Halophytic species are gradually replaced by terrestrial species until a successional climax is achieved. The resulting species composition, community structure and plant biodiversity is controlled by the frequency of inundation, salinity and the depth to the fresh-water table (Hayden *et al.,* 1995), usually with some degree of overlap between the tolerances of different species (Ranwell, 1972; Zedler and Beare, 1986). For example, production of *Spartina alterniflora* is limited by the slow movement of soil water and low light levels due to increased inundation (Hubbard, 1969; Wiegert, 1986) but can be increased by the circulation of nutrients as a consequence of increased tidal range (Steever, *et al.,* 1976).

The dominance of a particular species on a marsh may determine the resultant amount of sediment accretion. For example, creek margin *Halimione* accounts for the high rates of sediment accretion on both Sado Estuary (Portugal) (Moreira, 1992) and Norfolk marshes (French and Spencer, 1993). The accretion due to *Salicornia* and *Puccinellia* is documented at 3 cm y^{-1} and 10 cm y^{-1} respectively (Ranwell, 1972). In Louisiana marshes, Nyman *et al.,* (1995) attributed enhanced sedimentation in *Juncus roemerianus* stands compared to *Spartina alterniflora*, to the greater stem density of the former species. Maximum sedimentation on some marshes, occurring at mid-marsh levels, is attributed to the increased incidence of vegetation encouraging both deposition and stabilisation of fresh sediment (Randerson, 1979; Williams and Hamilton, 1995). Sedimentation rates will be related to other factors such as tidal inundation and sediment supply as well as the vegetation type, but there does appear to be a statistical relationship between the height of marsh and vegetation species that gives rise to differences in accretion rates in different parts of the marsh (Ranwell, 1964a; French and Spencer, 1993). Whether this is due simply to the vegetation or to hydroperiod and sediment supply, is not certain. Indeed Ranwell (1964a) suggests that increasing accretion can be associated with increasing height of marsh, height and weight of vegetation and increasing vegetation density but not to any one of these factors specifically, demonstrating the complex relationship between these factors within a saltmarsh system.

2.2.6 Erosion of saltmarshes

The geomorphology of saltmarshes is not only related to the spatial variations in sedimentation rates and accretion. Marshes also exhibit cyclic development with alternating periods of erosion and accretion occurring in response to a number of environmental conditions (Gray, 1972; Pringle, 1995). Marsh morphology is considered by Pethick (1992) to be "the attainment of an equilibrium between stress and strength: the physical expression of the critical erosion threshold". The onset of an erosional phase may be due to increases in relative sea level, a change in the exposure of the marsh (e.g. Harmsworth and Long, 1986; Pye, 1995) or a reduction in sediment supply (Williams and Hamilton, 1995). For example, vertical depletion resulting from plant die-back, is presently occurring in the Louisiana marshes because of sea-level rises. Greensmith and Tucker (1966) interpreted the erosion of the marsh edge as compensation for sediment starving of the fronting mudflats due to local changes in offshore current patterns.

Marsh deterioration can occur via a number of different methods, resulting in either vertical or lateral removal of sediments. Storms can increase marsh sedimentation in some environments but they can also damage marshes. The extent of damage varies considerably, depending on the intensity and direction of the storm. A single storm, circulating around a low pressure centre, has the capacity to promote both sedimentation and erosion within one marsh system (Nyman *et al.,* 1995) depending on whether the wind is blowing off-shore (lowering water levels) or on-shore (increasing water levels). A distinction was made by Wray *et al.,* (1995) on the varying impact of storm intensity on the marsh edge. During small storms, waves attack the marsh edge, breaking off any loose blocks, resulting in recession of the edge. During larger storms, in which water over-tops the marsh, the wave energy is dissipated across the marsh surface, resulting in reduced erosion.

Storms can destroy vegetation by uprooting and stripping (Chabreck and Palmisano, 1973), leaving marsh sediment without stabilisation. Pethick (1992) suggests that the geomorphological response by saltmarshes (and the fronting tidal flat) to storms is an increase in the length of the full intertidal profile. This is achieved by a decrease in the elevation of the saltmarsh and concomitant increase in the elevation of the tidal flat. This response increases the distance of the intertidal profile over which storm waves must travel, increasing the dissipation capacity of the system. Erosion of the saltmarsh, in this instance, feeds the accretion of the tidal flat. Pethick suggests that this reciprocal response of the tidal flat and the marsh exists during storm and non-storm periods. In this respect, the marsh provides a store of sediment which can be released to mitigate the impact of storms, as occurs on most foreshores and beaches. In contrast however, Leonard *et al.* (1995b) note that storms increase marsh sedimentation by mobilising sediment which has previously been removed from the marsh and deposited in the low intertidal zone, during ebb dominant flow conditions.

A familiar sight on many British saltmarshes, especially in the Severn Estuary, Morecambe Bay and the Solway Firth is a series of steps on the marsh surface generally considered to be evidence of frontal marsh erosion (Allen, 1989), although Pethick (1992) suggests they may also be determined by variable sedimentation rates of the vegetated marsh surface and the fronting tidal flat or even small changes in sea level (Hansom, 1988). Increased wave action, through changes in local or global conditions, and storminess may increase the erosion of the marsh edge, causing lateral depletion. Erosion of the marsh edge can occur in a number of ways depending on the sediment texture and stratigraphy, vegetation cover and moisture content of the soil. Cliffs with a sandy substrate overlain by a cohesive silty-clay layer will be quickly undermined because the shear resistance of sand is far less than that of clay (Van eerdt, 1985). The shear resistance of the sandy layer increases with greater cliff height because of an increase in the compressive strength of the sandy layer (Van eerdt, 1985). Moreira (1992) and Allen, (1989), noted that erosion occurred via undercutting and eventual collapse on marshes with a dense vegetation cover whereas on bare marshes, erosion was via rotation sliding on wet soils and block collapse on dry soils. Muddy marshes with a thin vegetation cover are eroded via toppling failures and rotational slips. Collapse of the marsh edge as the result of toppling is promoted by the development of deeply penetrating desiccation cracks during extreme low flow conditions prevalent in the summer months (Allen, 1987b). Cliff edge erosion occurs more frequently during the winter months when sediments become weaker because of wetting, via rainfall, and increased storm induced wave action.

It is generally projected that increasing sea level, due to climatic change, will result in erosion of saltmarshes (Hansom *et al.,* 2000). In areas where the rate of sea level rise is greater than the sedimentation rate, marshes will deteriorate as a result of the drowning of vegetation (Reed, 1995). The impact on marshes in micro- rather than macro-tidal systems may be greater because of the relative magnitude of change in tidal flooding affecting the marsh (Reed, 1995). In addition to rapid sea level changes, global warming may also increase the frequency of storms (Allen, 1992b). This will impact upon different marshes in different ways depending on their current mode of sedimentation. Marshes which rely on storm sedimentation may be able to accrete enough sediment to withstand sea-level rise. For those marshes, however, which erode during storms, the outlook may be bleak. Erosion, however, is not the only scenario and marshes which are able to accrete at a higher rate than the rise in relative sea level (taking into account rates of regional subsidence and marsh compaction) will continue to survive, making these marshes key components in coastal defence (Woolnough *et al.,* 1995).

Material which has been eroded from the edge of the marsh, or from the banks of a creek will either be washed away or will remain in front of the eroded site, protecting it against further erosion (Letzsch and Frey, 1980; Van eerdt, 1985; Allen, 1989). Ironically, the erosion of the marsh edge and creek banks can promote further sedimentation (Allen, 1989) by trapping sediment both in the spaces between the fallen blocks (Letzsch and Frey, 1980) and by vegetation which continues to grow on the blocks for a number of years (Pringle, 1995). In many instances, erosion of one part of the marsh may fuel accretion for another part (e.g. Marshall, 1960-61; Reed, 1988), indeed present thoughts towards managed retreat on saltmarshes relies in part on this process (Hansom, *et al.,* 2000).

2.2.7 Summary of saltmarsh development

Spatial variability in the deposition of sediment on a saltmarsh has a number of controlling factors, including hydroperiod, vegetation, elevation and geomorphology. The relative importance of these and their degree of inter-relatedness is still the subject of debate. It can be concluded that on tidally dominant marshes that are accreting via inorganic sedimentation, elevation is a strong control on long term sedimentation rates. This observation, however, may not be entirely valid in the short term, where proximity to creeks is often deemed more important, or on micro-tidal marshes, which rely on organic accumulations. The role of vegetation, both in terms of its capacity to trap sediment and as an autochthonous source of sedimentary material, changes with elevation, the species present and the health of the vegetation.

Deposition rates on many marshes have been measured at isolated points but few data sources exist on the spatial patterns of deposition rates and grain size characteristics, measured by either transects or areal survey (Woolnough, *et al.,* 1995). Until this has been done, the relationship between the controlling factors mentioned above will neither be fully understood nor established beyond doubt.

2.3 Methods used to measure sedimentation patterns in saltmarshes

The investigation of the sedimentary status of marshes involves measurement of both vertical and lateral changes over time. Such changes have been investigated on a number of different scales, depending on the spatial and temporal resolution required in the study.

Studies of vertical change conducted at a small scale involve measuring suspended sediment fluxes through creek systems over individual tidal cycles (e.g. Reed, 1987). These are extremely difficult to carry out because of the large variations in sediment load and discharge over a small time period. Careful consideration of the temporal sampling methods adopted in these studies is crucial because of velocity variations within any one tidal cycle (Bayliss-Smith, *et al.,* 1979; Reed, 1987). In addition to sampling, French, *et al.* (1995b) identify further problems with estimates of sediment flux, where firstly, sediment storage occurs within channel systems and secondly, where the tidal exchange of sediment does not occur via the creek system.

A number of methods have been used to determine vertical changes in saltmarsh surfaces over short time periods (<10 years). Studies of marshes in north Norfolk used sand marker horizons applied to the marsh surface to record rates of deposition (Stoddart, *et al.,* 1989, French and Spencer, 1993). Similarly, use has been made of feldspar (Cahoon and Reed, 1995, Cahoon *et al.,* 1996), brick dust (Moreira, 1992) and aluminium glitter (Harrison and Bloom, 1977) to create artificial horizons from which to measure sedimentation rates. These methods are appropriate if there is negligible bioturbation of the sediment (Leonard, *et al.,* 1995a). Burd (1996) used buried metal plates to measure changes at fixed positions over time, in a study of marsh restoration at Northey Island in the Blackwater Estuary. This method has also been employed by Pethick (1992) and Möeller (1997). While there are still issues of sampling to consider, these methods have proved useful in gaining an insight into the spatial and temporal variability of sedimentation, including the role of storms, marsh topography and creek hydrodynamics (French, *et al.,* 1995b; Roman, *et al.,* 1997). These methods can accurately measure the rate of sedimentation over short timescales but are less appropriate for determining the overall elevation change of the marsh because they do not take into account compaction of the marsh substrate (Cahoon, *et al.,* 1995). This may not be considered a problem if consolidation of the sediment occurs regularly due to the marsh drying out, either because of low rainfall and high temperatures during the summer or by tidal exposure (Allen, 1992a).

Determining historical sedimentation rates requires identification of a datable horizon in the sediment. Allen (1988) used historical variations in pollutant input to establish the rates of sedimentation in the Severn Estuary. Many workers have used radioactive nuclides such as anthropogenic ^{137}Cs from nuclear weapons testing fallout, (e.g. DeLaune, *et al.,* 1978; 1983, Hatton, *et al.,* 1983; Oenema and DeLaune, 1988; Craft, *et al.,* 1993; Hutchinson and Prandle, 1994; Kearney, *et al,* 1994; Milan, *et al.,* 1995) or natural ^{210}Pb (Sharma, *et al.,* 1987, Brenner, *et al.,* 1994, French *et al.,* 1994) to measure sedimentation rates in marsh and estuarine environments. Other sources of anthropogenic radionuclides have been used in saltmarsh sedimentological studies, for example ^{137}Cs from the Sellafield in Cumbria (e.g. Aston and Stanners, 1979, Stanners and Aston, 1981a, b, Clifton and Hamilton, 1982, Allan, 1993) and fallout from the Chernobyl nuclear accident (Callaway, *et al.,* 1996). These methods are criticised by French *et al.* (1995b) where the sedimentation rates are time dependent, as in the case of macro-tidal marshes experiencing inorganic sedimentation, where sedimentation occurs rapidly following the establishment of vegetation but declines progressively towards an asymptote.

Surprisingly few authors (French, *et al.,* 1995b; Roman, *et al.,* 1997) have integrated the use of the methods outlined above, despite the usefulness of having complementary information at different timescales. For example, measurements taken over two or three years will verify (or otherwise) accretion rates determined by longer term studies, as well as clarifying spatial variations.

The measurement of lateral changes in marshes has not received as much attention as vertical changes. Much of this kind of work has been conducted using archive maps and aerial photographs, discussed in Chapter three. For example, the sinuosity of creeks on some north Norfolk marshes has been monitored using aerial photographs taken at different dates (Pye, 1992). A typical way of measuring coastal erosion is to position stakes or pins along the coast, and survey these from some known datum point (e.g. Lorang and Stanford, 1993) with successive surveys revealing the extent of change. This method has problems. Firstly, there is a danger, on a rapidly eroding marsh, that the pegs or pins will be eroded away. Secondly, on accreting coasts, the pins may be covered by the advancing marsh. Finally, the existence of a network of pegs at the marsh edge may distort the existing sedimentation pattern, since the pegs may provide a locus for the deposition of sediment on the marsh surface or cause small eddies to be formed in the incoming tide, resulting in accelerated erosion (Plate 2.1). Which, if any, of these processes occurs depends on the prevailing conditions of the marsh. This situation was partly overcome by Ranwell (1964a) who used bamboo canes to measure the accretion on a *Spartina* marsh, arguing that the cane, being of a similar diameter to *Spartina,* would behave in a similar way. This is an appropriate technique only where vegetation swards are monospecific and are of similar dimensions to the cane.

Plate 2.1 Erosion around base of peg

The following part of this review seeks to demonstrate that radionuclides from the Sellafield Nuclear Fuel Reprocessing Plant (Sellafield) discharged into the Irish Sea are transported onto saltmarshes along the entire Irish Sea coast and can be used for a variety of sedimentological investigations. Before this can be done however, it is important to establish the source of the radionuclides, their behaviour in the natural environment and their method of transport within the Irish Sea. It is also important to establish the limiting factors in using radionuclides as an investigative tool.

It should be noted that the incidence of anthropogenic radionuclides in the environment is considered not only as a tool but also as a concern. Mention will therefore be made of the fate of radionuclides in the Irish Sea area, the inventories which have been calculated to date and problems of monitoring radionuclides in coastal and intertidal areas.

ANTHROPOGENIC RADIONUCLIDES IN THE COASTAL ENVIRONMENT

2.4 Background Information

2.4.1 Sources of anthropogenic radionuclides

Sources of radionuclides introduced into the environment by human action can be considered as either global or local in extent. Global sources are distant sources which have introduced low level contamination on a world wide scale, whereas point sources introduce local high levels of contamination. The largest global source has been from atmospheric nuclear weapons testing which occurred with greatest intensity in the years 1957-58 and 1961-62. Whilst no atmospheric testing of nuclear weapons has been carried out since 1980, a small amount of residual radioactive material from earlier tests continues to fall out, affecting both terrestrial and aquatic environments. The most important of the fallout radionuclides (in terms of activity) are shown in Table 2.1, although there are many other transuranic elements and fission products at lower activities within the fallout. The Chernobyl accident in 1986 was the second most important contributor of anthropogenic radionuclides to the atmosphere. Radioactive material from this accident, which occurred as a result of an explosion and fire in a high powered nuclear reactor, spread over the entire northern hemisphere (Voigt, 1997). In the UK, contamination from Chernobyl was deposited predominantly in areas where rain intercepted the radioactive plume, for example in south-west Scotland, Cumbria, north Wales and Northern Ireland (DoE, 1992).

Other nuclear accidents have contributed smaller quantities of radionuclides to atmospheric and aqueous environments, for example Windscale (1957), Kyshtim (1957) and Three Mile Island (1979), although their impact was more important at a local level. A final source of global anthropogenic radionuclides comes from satellite failures, the most significant of which, was SNAP-9A which burned up over the South Atlantic Ocean in 1964. This satellite, containing one kilogram of ^{238}Pu (used as a power source for the inboard computers), became a globally significant source of ^{238}Pu contamination, particularly in the southern hemisphere (Aarkrog, 1997).

Event	^{137}Cs	^{131}I	^{90}Sr	^{106}Ru	^{144}Ce	$^{239,240}Pu$
Nuclear tests 1952-1962	910	$6.5x10^5$	600	$1.2x10^4$	$3.0x10^4$	11
Chernobyl, 1986	70	670	8	30	140	0.07

Table 2.1 Releases of some important radionuclides into the environment (PBq) (taken from Balonov, 1997)

Local sources of anthropogenic radionuclides come largely from nuclear power and reprocessing installations which discharge low level radioactive wastes into both the atmosphere and coastal or estuarine waters. The production of nuclear energy is based mainly on the fission of natural and anthropogenic ^{235}U. Only 0.7% of natural uranium is present as ^{235}U which is readily fissionable, while ^{238}U which comprises 99.28% of natural uranium is not fissionable. A large number of radionuclides are produced during nuclear fission (fission products) and by concomitant neutron capture reactions (activation products). During nuclear energy production, these fission and activation products accumulate, reducing the efficiency of the fuel, such that it needs to be replaced after only a small fraction of the ^{235}U has been used. In the United Kingdom, the spent fuel rods are then reprocessed to separate the unused ^{235}U and ^{239}Pu (produced via irradiation of ^{238}U) from the fission and activation products. Waste materials from both nuclear energy production and spent fuel reprocessing will contain both fission and activation products.

Low level wastes (LLW) constitute the greatest bulk of radioactive waste material from nuclear facilities but give rise to only about 1% of the radioactivity (Kathren, 1984). The U. K. Department of the Environment, (DoE, 1992) describes LLW as "material arising from the operation of nuclear facilities which has a low radionuclide content and which does not require shielding during normal handling and transport". Low level waste can come from a variety of sources and can exist in liquid, gaseous and solid forms. Solid forms are stored on site or in authorised landfill sites, such as Drigg in Cumbria and include plastics, paper, scrap metal, protective clothing and excavation spoil (DoE, 1992). Gaseous forms are emitted into the atmosphere. These can be subject to rapid dispersion and result in rapidly diminishing ground levels of radioactivity away from the source of output (Pierson *et al.,* 1982). Liquid forms are often treated prior to discharge into water bodies. The dispersion of the discharge in the aquatic environment depends on the biogeochemical behaviour of radionuclides released and the chemical nature and circulation pattern of the receiving waters.

2.4.2 Discharge of radionuclides from the Sellafield Nuclear Fuel Reprocessing Plant

By far the most important contributor of contaminant radioactive material to the coastal environment around the British coast is the Sellafield Nuclear Fuel Reprocessing Plant (henceforth Sellafield) in Cumbria which, since 1952, has discharged low level liquid radioactive waste, under authorisation, into the Irish Sea (Figure 2.2 for location map). Discharge occurs via two steel pipes which extend 2500 m seawards beyond the mean high water springs (MHWS) mark ending in approximately 20 m of water. The discharged effluent comes from two main sources: water used continuously to clear the ponds in which spent nuclear fuel elements are stored to cool before being reprocessed and; other sources on site which are routed through sea tanks before being discharged. Water from the ponds is treated at the Site Ion Exchange Plant (SIXEP) which removes the bulk of fission and activation products, particularly ^{134}Cs, ^{137}Cs and ^{90}Sr before being discharged. The sea tank effluent, which is also treated, is the major source of transuranium nuclides (for example, ^{241}Am and Pu isotopes) (Pentreath, *et al.,* 1984).

For the remainder of this thesis, the focus will be on ^{137}Cs and ^{241}Am, although plutonium isotopes will be mentioned where relevant. These nuclides have relatively high activities in the discharge combined with long half-lives (^{137}Cs and ^{241}Am half lives are 30.23 and 458, years respectively) making them of radiological concern. The fact that they are long-lived radionuclides also makes them especially useful in investigating saltmarshes and they are easily identified and measured in the laboratory.

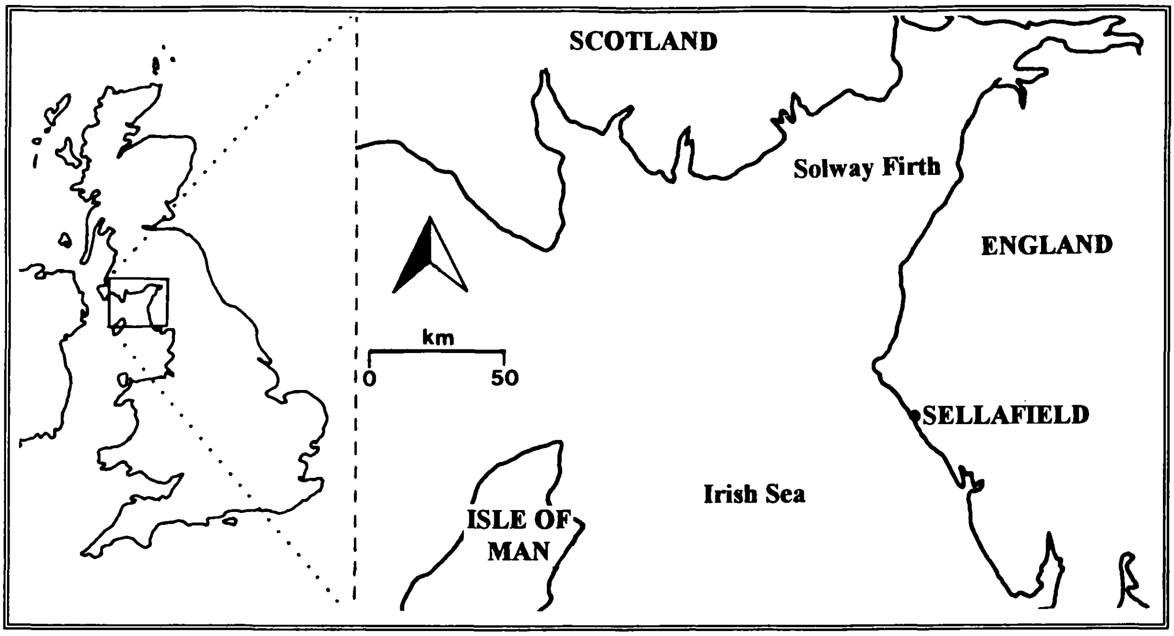

Figure 2.2 Location Map for Sellafield

Discharges of both ^{137}Cs and ^{241}Am have varied over the last 40 years (Table 2.2, Figure 2.3). In addition to direct discharge from Sellafield, an appreciable quantity of ^{241}Am also results from the decay of discharged ^{241}Pu (half-life 14.35 years). During the early and mid 1970s discharge levels of both radionuclides increased due to greater throughput and the reprocessing of more highly irradiated fuel. Reductions in total discharges from Sellafield after this period occurred due to more effective techniques in removing radionuclides from the waste effluent prior to discharge, such as SIXEP (Site Ion Exchange Effluent Plant) and EARP (Enhanced Actinide Removal Plant) operating from 1985 and 1994 respectively, and the imposition of lower authorisation limits (Hunt *et al.*, 1996).

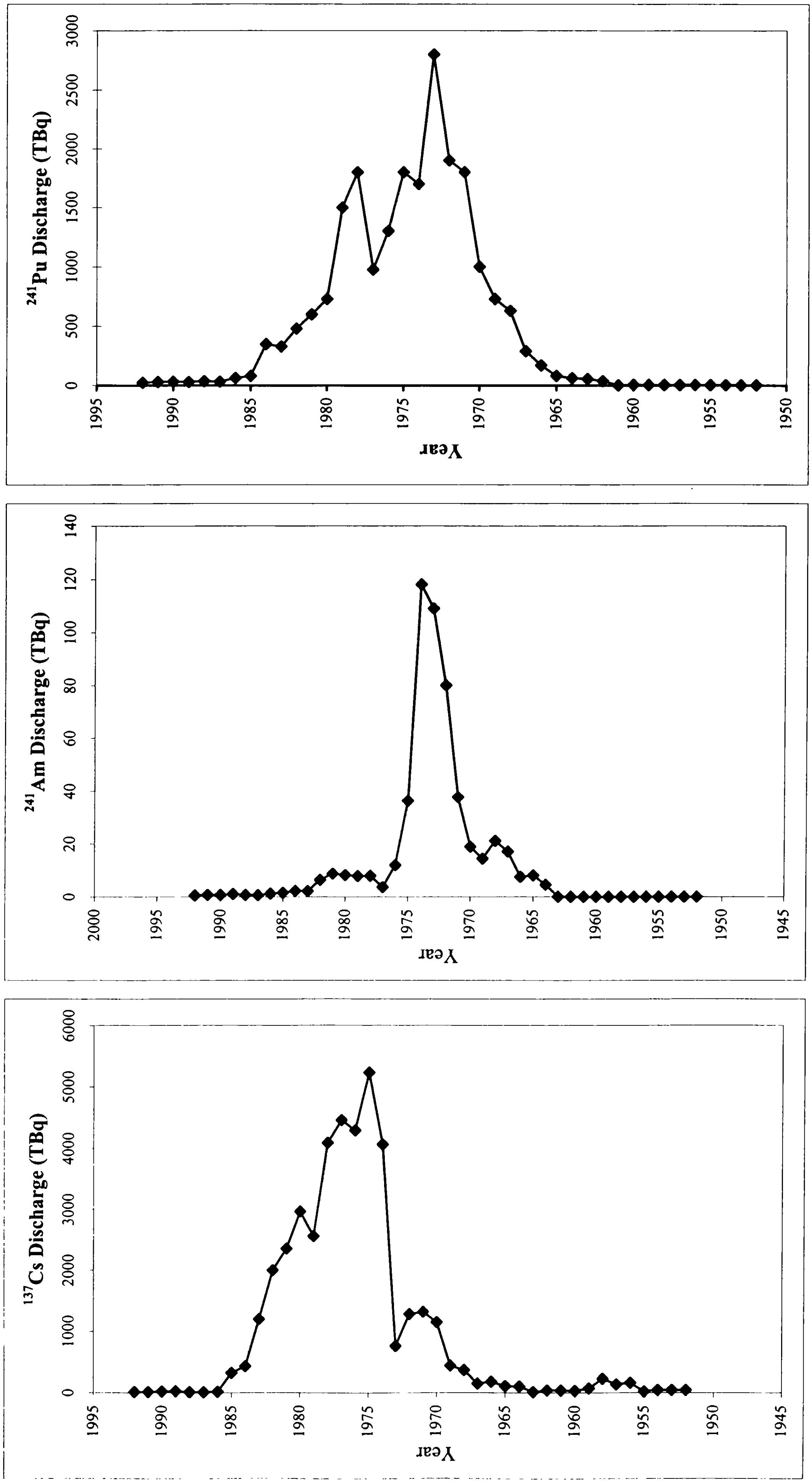

Figure 2.3 Discharges of ^{137}Cs, ^{241}Am and ^{241}Pu from Sellafield (Gray, *et al.*, 1995)

Year	^{137}Cs (TBq)	^{241}Am (TBq)	^{241}Pu (TBq)	Year	^{137}Cs (TBq)	^{241}Am (TBq)	^{241}Pu (TBq)
1952	46	0.0	2.0	**1973**	768	109	2800
1953	46	0.0	1.0	**1974**	4061	120	1700
1954	46	0.0	2.3	**1975**	5231	36	1800
1955	21	0.0	1.9	**1976**	4289	12	1300
1956	164	0.0	3.7	**1977**	4458	3.7	980
1967	138	0.0	3.4	**1978**	4088	7.9	1800
1968	229	0.0	3.9	**1979**	2562	7.8	1500
1959	73	0.0	4.4	**1980**	2966	8.2	730
1960	34	0.0	6.2	**1981**	2357	8.7	600
1961	40	0.0	18	**1982**	2000	6.4	480
1962	74	0.0	37	**1983**	1200	2.2	330
1963	85	0.0	55	**1984**	434	2.3	350
1964	104	4.5	62	**1985**	325	1.6	81
1965	110	8.1	81	**1986**	18	1.3	63
1966	181	7.5	170	**1987**	12	0.65	32
1967	150	17	290	**1988**	13	0.75	36
1968	372	21	630	**1989**	29	1.1	30
1969	444	14	730	**1990**	24	0.75	32
1970	1154	19	1000	**1991**	16	0.74	30
1971	1325	38	1800	**1992**	15	0.54	25
1972	1289	80	1900				

Table 2.2 Annual liquid effluent discharges of ^{137}Cs, ^{241}Am and ^{241}Pu from Sellafield (Gray, *et al.*, 1995)

2.4.3 Fate of radionuclides entering the Irish Sea

The discharge of low level radioactive liquid waste into the sea, to satisfy waste disposal legislation, depends upon achieving adequate dilution of the effluent (Jefferies, *et al.*, 1973). The potential for dilution varies between conservative and non-conservative radionuclides. Conservative radionuclides, for example ^{137}Cs, remain in solution while non-conservative species, for example ^{241}Am and Plutonium isotopes are rapidly removed from the water column by sorption* to particulate material. There is a continuum of behaviour between highly conservative and highly non-conservative species.

Hetherington, *et al.* (1975) determined that most of the ^{137}Cs discharged is retained in aqueous form. The movement, behaviour and subsequent concentrations of ^{137}Cs within the Irish Sea and beyond, has been investigated by numerous authors (e.g. Livingston and Bowen, 1977; McKinley, *et al.,* 1981a, b; Howarth, 1984). The net movement of dissolved ^{137}Cs in the Irish Sea is northwards associated with residual currents. This has resulted in concentrations of ^{137}Cs being 20 times higher in the North Channel of the Irish Sea than in St. George's Channel. The southerly movement of radionuclides is driven by storm-induced wave action of surface waters (Howarth, 1984). From the North Channel, ^{137}Cs is dispersed through the Minch, via Cape Wrath and the Pentland Firth and into the North Sea, where it can be detected as far south as the north-east of England (Jefferies, *et al.,* 1973). Pattenden and McKay (1994) demonstrated that concentrations of ^{137}Cs in seawater in the Pentland Firth had fallen during the 15 year period prior to 1994, reflecting the reduction in the discharges from Sellafield. This highlights the dominant influence of Sellafield in northern waters, in spite of the proximity of the Dounreay reprocessing plant which also discharges low level liquid radioactive waste. The time taken for ^{137}Cs to travel from Sellafield to the northern parts of the Clyde Sea has been calculated as about eight months (McKinley, *et al.,* 1981a).

Of additional concern are those radionuclides which are not transported out of the Irish Sea in seawater, but are sorbed onto particulate material and enter the sediment system. In this instance, it is the physical and chemical behaviour of the sediments and their interaction with radionuclides which determines the dispersal paths of the effluent. A useful measure of the efficiency with which sediment retains radionuclides is the

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* Sorption is used as a non-specific term describing the process of taking up and holding (radionuclides) either by adsorption or absorption. These processes are often difficult to separate in practice. Adsorption is the process of taking up (radionuclides) on the surface, while absorption is the process of taking up within a particle (Sayre, *et al.,* 1963).

partition coefficient (K_D) which is defined as the ratio of the specific activity in the sediment to that in the seawater (Smith *et al.,* 1980). Thus, the higher the K_D, the greater the potential for a radionuclide to adsorb to sediments. These values must be used with care because they can change, depending on the conditions prevailing in the environment of interest.

While it has been shown that most of the ^{137}Cs discharged from Sellafield remains in the aqueous phase, some is retained by clay minerals, in particular by illite and chlorite and to a lesser extent by kaolinite and montmorillonite (Smith, *et al.,* 1980). MacKenzie *et al.* (1990) estimated that between 9 - 17% of the discharged ^{137}Cs was taken up by the Irish Sea sediments, while Jefferies and Steele (1989) put the figure at about 10%. K_D values reported for ^{137}Cs range between 10^2 and 10^3 for the Clyde Sea (Baxter *et al.,* 1979) and 10^3 in the Irish Sea (Kershaw *et al.,* 1992) . Francis and Brinkley (1976) showed that ^{137}Cs is adsorbed into the layers of micaceous minerals and becomes trapped as the clay lattice collapses, making ^{137}Cs unavailable for subsequent uptake by biological organisms. It has, however, been shown that ^{137}Cs sorption to Irish Sea sediment is reversible, with up to 75% re-dissolution by 1991, of ^{137}Cs that was initially taken up by surface sediments in the 1970s and 1980s (Hunt and Kershaw, 1990, McCartney *et al.,* 1994, MacKenzie *et al.,* 1994). Stanners and Aston (1981b) observed that ^{137}Cs is adsorbed by Irish Sea sediments by an ion-exchange reaction which involves competition with other alkali metal ions, especially K^+. Nishita *et al.* (1965) state that ^{137}Cs, as a result of this competition, is more strongly sorbed to soils with K^+, explaining the affinity of ^{137}Cs for illite which is a hydrous *potassium* silicate ($KAl_2(AlSi_3)O_{10}(OH)_2$), as opposed to other clay minerals which contain varying amounts of aluminium and magnesium cations. The significance of this becomes apparent in light of the fact that upwards of 75% of clay minerals in the central north-eastern Irish Sea are of the illite group with lesser concentrations of chlorite and kaolinite (Cronan, 1970).

Transuranic elements undergo strong sorption by sediments. Pentreath *et al.* (1984) estimated K_Ds for a number of radionuclides placing them in the order: Am and Cm > Pu > Np. Livingston and Bowen (1977) measured a greater proportion of plutonium than ^{241}Am in the Minch and attributed this to the association of ^{241}Am with sediments during transportation in coastal waters. The K_D value for Am is 10^6 (Kershaw *et al.*, 1992). Given that 95% of plutonium activity discharged is thought to be lost from the water to the sediment phase almost immediately after discharge (Hetherington, 1976) and that the K_D value for ^{241}Am is greater than the average for Pu, it can be assumed that at least the same or a greater percentage of ^{241}Am activity will also be lost to sediments near the outfall pipe. The specific method by which ^{241}Am is sorbed to particles is not clear. Aston *et al.* (1981) found that between 75-100% of the plutonium in Ravenglass sediments was associated with the Fe/Mn hydrous oxide phase of the sediments, although a much lower value was measured for sediments from the Wyre estuary. This association has been confirmed by Livens and Baxter (1988) and Allan *et al.*, (1991). It is presumed by Assinder (1983) that this is also the case for ^{241}Am.

Although most of the discharged Pu and ^{241}Am is taken up by sediments, these nuclides have been detected in a soluble state in northern coastal waters. In the case of Pu this is because of the different oxidation states in which it can exist. For example, Pu(III, IV) is readily adsorbed by sediments (K_D = 10^6), whereas Pu(V, VI) is more soluble in seawater (K_D = 10^4) (K_D values from McKay and Pattenden, 1993). ^{241}Am however, exists in seawater only as Am(III) and is readily lost to sediments. It is suggested by Day and Cross (1981) that the ^{241}Am measured in northern coastal waters results from the ingrowth of ^{241}Am produced from ^{241}Pu, which has been transported northwards in a conservative oxidation state in the dispersal plume (in the same manner as ^{137}Cs described above).

Numerous authors illustrate a positive relationship between ^{241}Am concentrations and the percentage of fine particle sizes in sediment (for example, Aston and Stanners, 1981; Clifton and Hamilton, 1982; Pentreath *et al.*, 1984; McKay and Pattenden, 1993, McCartney *et al.*, 1994). This relationship also holds for ^{137}Cs (for example, Smith, *et al.*, 1980; Stanners and Aston 1981b; Aston and Stanners, 1982a, b; Jones *et al.*, 1984). There is also an apparent relationship between the organic carbon content of sediment and radionuclide concentrations but this may again be a particle size effect, with high values of organic carbon associated with the finest sediments (Hetherington, 1978;

Aston *et al.,* 1981; Assinder, 1983). Cundy and Croudance (1995) measured high values of ^{137}Cs in coarse size fractions only when there was an associated enrichment of organic carbon. Associated with the carbon were appreciable amounts of Al_2O_3 and K_2O indicating the presence of clay minerals, suggesting that high ^{137}Cs activities are related to the clay minerals rather than the organic matter. Such is the strength of the radionuclide/sediment size relationship, that Aston *et al.* (1981) and Assinder (1983) all suggest that sediment size can be used as a reliable indicator of radionuclide concentrations and further, Aston, *et al.* (1985) suggest that the highest activities are predictably in those areas where the finest mud accumulates. This relationship also means that the movement and fate of fine sediments within the Irish Sea must be determined before sense can be made of radionuclide concentrations.

2.4.4 Fine sediment sources and sinks in the Irish Sea

The above discussion points to the association of some ^{137}Cs and the majority of ^{241}Am with fine grained sediments. In order to establish the fate of these radionuclides it is important to determine the source and movement of fine grained sediments within the Irish Sea. It is therefore essential to establish the sedimentology of the Irish Sea before discussing the movement of Sellafield radionuclides associated with these sediments.

Investigations of sea floor sediments in the eastern Irish Sea point to the existence of a large area, approximately 40 km long, parallel to Cumbrian coast and 10 km wide, of fine grained sediment in the vicinity of the Sellafield outfall pipes (Cronan, 1969 (Figure 2.4); Pantin, 1977, 1978).

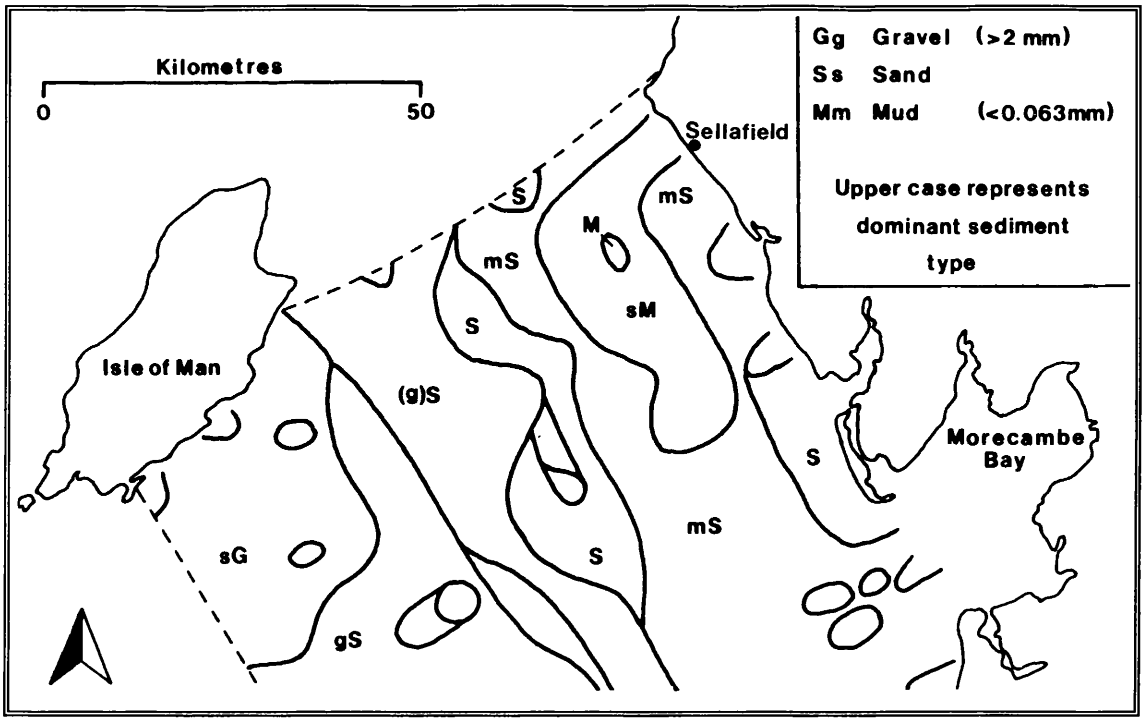

Figure 2.4 Map of the main sediment types in the eastern Irish Sea (from Cronan 1969)

Uncertainty exists as to whether this area of fine sediment is accreting, eroding or stable. If accreting, the sediment would act as a sink for radionuclides discharged from Sellafield, with the high levels of radioactivity discharged during the 1970s eventually being buried. If eroding, radionuclides associated with the fine sediments would be redistributed, increasing the likelihood of an exposure pathway to humans being established if on-shore transport was significant.

One view is that recent accretion is occurring, the result of a number of supply sources (Belderson, 1964; Belderson and Stride, 1969; Cronan, 1969; Pantin, 1977, 1978; Nunny, 1978). The Permo-Triassic bedrock of the Irish Sea Basin is overlain by glacial till, (Pantin, 1977) deposited towards the end of the Devensian glaciation. Above the till lies a series of well bedded sediments (tens of metres thick) which were deposited in a pro-glacial environment. Above these lie 'marine beds' (Pantin, 1977, 1978), designated SL2 (lower bed) and SL1 (upper bed) deposited, respectively, on beaches or tidal flats and subtidally. It is postulated that material from SL2 supplies the SL1 sedimentary sequence because of exposure of parts of the SL2 bed in the western Irish Sea.

Two areas of sedimentation are identified by Pantin (1977): an area of extensive muds off the Cumbrian coast and Morecambe Bay, extending north to the Solway Firth; and, an area of mud lying SW of the Isle of Man. The latter is supplied with sediment eroded from east of Wicklow (Ireland) (Stride, 1963; Belderson, 1964). The former is supplied with sediment originating in St. George's Channel (Cronan, 1969) and from SL2 and SL1 deposits south-west of the Isle of Man (Pantin, 1978). Sediment originating in St. George's Channel and in the North Channel is moved eastwards, demonstrated by the existence of a series of sandwaves, into the Solway Firth and Liverpool Bay, with some deposition occurring in the mud bank off the Cumbrian coast (Belderson and Stride, 1969). The deposition of sediment is coincident with zones of low relative tidal energy (Cronan, 1969; Pantin, 1977).

While these processes may well be supplying sand sized sediment to areas of apparent accretion, the paucity of mud in SL2 beds means that they are unlikely to be the source of the large muddy areas identified by Cronan (1969) and Pantin (1978). In response to this, Pantin (1978) suggests a number of alternative sources of mud including supply by modern rivers, erosion of coastal cliffs, reworking of glacial till and pro-glacial sediments (which, unlike the marine beds, do contain appreciable amounts of mud) and muddy sediments in the Solway Firth - Wigtown Bay area. In addition to these sources, Nunny (1978) included the primary production of organic and skeletal debris and fine sediment from St. George's Channel.

Geological and sedimentological evidence for active sedimentation in the eastern Irish Sea is critically reviewed by Kirby *et al.* (1983) who conclude that such evidence is circumstantial. The main criticism lies with the source of fine sediments located off the Cumbrian coast. For example, there are a number of rivers which flow into the Irish Sea but the exact amount of sediment supplied by them is unknown. A number of the larger estuaries and bays in the Irish Sea area have extensive saltmarsh systems and are infilling with fine sediment rather than supplying it to the outer coast and marine environment Kirby *et al.,* 1983). The only coastal cliffs in the Irish Sea area which are being appreciably eroded are those between St. Bees and Duddon, sediment from which is thought to be deposited in local estuaries rather than transported into the Irish Sea.

Sub tidal sources (sediments eroded from St. George's Channel) are, claim Kirby *et al.* (1983), not proven.

Using a variety of techniques (radionuclide analysis, X-radiography, magnetic property analysis) to investigate cores taken from the Irish Sea, Kirby *et al.* (1983) present an alternative explanation for the evolution of the mud bank off the Cumbrian coast. Within the cores, the sediment was virtually homogenous with no remaining primary fabric (for example, bedding), the magnetic fabric of the sediment was disturbed and the radionuclide analyses showed profiles inconsistent with the sequential settling of sediment. Three types of core were subsequently identified and interpreted as demonstrating different stages of sediment mixing as a result of bioturbation. This interpretation concurs with the results of Kershaw *et al.* (1983) whose analysis of $^{238}Pu/^{239,240}Pu$ activity ratios indicated two types of core representing different stages of bioturbation by organisms including *Maxmuelleria lankesteri*, an echiuroid worm, which burrows to depths exceeding 40 cm, and the Thalassinid shrimp *Callianassa subterranea*. Bioturbation homogenises sediment in the upper layers of the sea bed, thereby mixing contemporary, low activity sediments, with older, high activity sediments. The intensity of bioturbation makes it very difficult to establish whether the eastern Irish Sea is eroding or accreting (Pentreath, *et al.*, 1984). Further evidence of sediment mixing comes from Kershaw (1986) who uses ^{14}C dating to show that the sediments off the Cumbrian coast have not been recently deposited, but rather have been extensively reworked.

Dyer (1986) presents a model for the Cumbrian mud patch which agrees with the interpretation of Kirby *et al.* (1983). Dyer (1986) suggests that the surface of the mud patch is highly mobile due to extrusions from burrowing organisms and from deposition of sediment after storm activity. This sediment is easily entrained during subsequent stormy weather and is redeposited in other areas of the mud bank. This recycling hypothesis provides an apparent solution to the problem of the source of fine grained sediment.

The situation, however, is further complicated by Kershaw *et al.* (1988) who derived an upper limit for the (very low) accumulation rate of sediment in three locations within the

Irish Sea mud belt. Although this accumulation may be occurring, a suitable source for the fine sediment is not presented, the suggestion being that sediment is transported from the Solway Firth-Wigtown Bay area. The Solway Firth, however, may be infilling with sedimentary materials (Perkins and Williams, 1966, Kirby *et al.,* 1983), rather than being a source of sediment. Kershaw *et al.* (1988) note that the present rate of sedimentation is insufficient to bury the radionuclides discharged from Sellafield and that, because of bioturbation, older, more highly contaminated, sediments will continue to be returned to the surface. These sediments may then be activated by the processes suggested by Dyer (1986).

This review of the sedimentology of the eastern Irish Sea shows that there are two views regarding sedimentation patterns in the area. One states that there is recent sedimentation, albeit at a very low rate, in the mud bank off the Cumbrian coast, while the other suggests that the apparent sedimentation is a result of recycling of older sediments through bioturbation, and that this sediment is being transported into the bays and estuaries along the eastern Irish Sea Coast. The latter argument is more convincing; an opinion which finds support in the following account of radionuclide distributions in the Irish Sea and Solway Firth. Whilst there is still ambiguity as to the exact sedimentary status of the eastern Irish Sea, the muddy area adjacent to the outfall pipes from Sellafield will continue to be a source, rather than a sink, of radionuclides to the surrounding environment for many years to come unless there is a change in the physical conditions within the Irish Sea.

But what is the fate of contaminated sediment in the Irish Sea?

2.4.5 The movement of fine sediment and radionuclides in the Irish Sea.

Many studies concerning the radiological impact of the Sellafield effluent discharge are concerned with the movement of radionuclides to areas of potential human contact. To this end, numerous studies have investigated intertidal areas around the Irish Sea and indicate conclusively that there is on-shore movement of radionuclides. The transport mechanism of radionuclides depends on the solubility of the particular species, considered as a continuum between conservative (remaining in the water column) and particle reactive (becoming rapidly associated with sediments). Thus there are two ways in which radionuclides can be transported to intertidal areas, namely: movement of contaminated water or contaminated sediment. These transport processes can be investigated using the ratios of different radioisotopes or radionuclides. Each transport mechanism (either solution or particulate) has a variety of characteristic ratios for various radionuclides (MacKenzie *et al.,* 1987). These reference ratios can be used to determine the transport mechanism for radionuclides found in the Irish Sea and its coast. The reference ratios have been calculated for each component of the Sellafield discharge. Ratios for the particle-associated component have been typified by Hunt (1985) investigating silts from Newbiggin, near Sellafield The soluble component ratios are calculated using published K_D values (MacKenzie, *et al.,* 1987; McDonald, *et al.,* 1990).

An example of this is given in Table 2.3 which compares measured isotopic and radionuclide activity ratios from intertidal sediments in the northern Irish Sea with the reference ratios for particular transport mechanisms. These results illustrate that the Solway Firth area (region A) is dominated by particulate transport, the northern North Channel (region C) is dominated by solution transport in addition to an observed influence of atmospheric fallout, while the south-west of Scotland (region B) tends towards particulate transport with an influence from both solution transport and atmospheric fallout. The transport, therefore, of radionuclides to coastal areas of the north-east Irish Sea is dominated by sedimentary processes but this influence diminishes with increasing distance from Sellafield.

The figures presented in Table 2.3 relate to activity ratios for Irish Sea surface sediments during the 1980's and they have since changed. For example, the $^{137}Cs/^{241}Am$ activity ratio has reduced to around 1 because of the ingrowth of ^{241}Am from the in situ decay of ^{241}Pu and redissolution of ^{137}Cs from surface sediments (MacKenzie *et al.,* 1999). Despite this change, the ratios are still compatible with particle rather than solution transport processes.

	$^{137}Cs/^{239,240}Pu$	$^{241}Am/^{239,240}Pu$	$^{238}Pu/^{239,240}Pu$	$^{137}Cs/^{241}Am$
Sediments				
Region A - Solway Firth	< 10	> 1	> 0.2	< 10
Region B - south-west Scotland	10 - 40	c. 1	c. 0.2	10 - 50
Region C - northern North Channel	> 40	< 1	< 0.2	> 50
Reference activity ratios				
Sellafield waste - particle-associated	1.9	1.04	0.24	1.8
Sellafield waste - soluble	35	< 0.28	0.31	> 125
Atmospheric fallout	56	0.23	0.05	240

Table 2.3 Comparison of observed ranges of activity ratios and reference activity ratios (from MacKenzie, *et al.*, 1987)

These results are corroborated by a linear relationship found between the concentrations of ^{137}Cs and ^{241}Am, and $^{239,240}Pu$ and ^{241}Am over a distance of 100 km in the northern Irish Sea. Had transport of the radionuclides occurred in solution, there would have been an exponential decrease in these activity ratios with distance (MacKenzie and Scott, 1993) because of the different efficiencies with which the radionuclides are sorbed to sediment (indicated by the K_D values) and the dilution of radionuclide concentrations as mixing occurs with less contaminated seawater. These results are confirmed by McDonald *et al.* (1990) investigating a number of marine cores along a transect from Sellafield to Kirkcudbright Bay in south-west Scotland.

If the transport of radionuclides to intertidal areas near Sellafield via particle transport is accepted, then in areas of active sedimentation, a profile of the Sellafield discharge, modified by any pre-depositional mixing, should be recorded in the accumulating sediment (assuming no post-depositional mixing by physical or biological processes). MacKenzie *et al.* (1994) demonstrate that while the pattern is qualitatively comparable to the Sellafield discharge, the variations in radionuclide concentrations with depth in the sediment are not linearly related to variations in actual quantities discharged from Sellafield. This discrepancy, investigated using the activity ratios of $^{238}Pu/^{239,240}Pu$, $^{134}Cs/^{137}Cs$ and $^{241}Am/^{239,240}Pu$, was attributed to intense offshore mixing of the discharged radionuclides prior to deposition, hence integrating discharges of different ages. Mixing of offshore sediment is also suggested by Jones *et al.* (1988) and McDonald *et al.* (1990), the latter using the ratio between ^{241}Am and ^{241}Pu. As well as being discharged directly from the Sellafield plant, ^{241}Am is produced from the decay of

^{241}Pu, so there will be an increase in the $^{241}Am/^{241}Pu$ ratio with time. McDonald *et al.* (1990) discovered that the $^{241}Am/^{241}Pu$ ratio for all samples along a transect of surface offshore sediment, from Sellafield to the south-west of Scotland, were similar to each other, implying that the sediment is well mixed prior to movement northwards from Sellafield. This also suggests that the northwards movement of radionuclides occurs on a timescale of years rather than decades (McDonald *et al.,* 1990). The sediment initially contaminated by the Sellafield discharge is subject to rapid, intensive vertical mixing by bioturbation (Kershaw *et al.,* 1983; 1988; Pentreath, *et al.,* 1984) resulting in a *time-integrated* signature of radionuclide concentrations and ratios in the sediment. Redistribution and subsequent deposition of this contaminated sediment would give an accumulation profile determined by the time-integrated Sellafield discharges rather than annual discharges (MacKenzie and Scott, 1993; MacKenzie *et al.,* 1994), modified by sediment mixing/dispersion and, in the case of ^{137}Cs, re-dissolution. Such profiles recording the Sellafield time-integrated discharge pattern have been found in a number of coastal locations, for example, the Esk Estuary (Aston and Stanners, 1979; Clifton and Hamilton, 1982), the Wyre Estuary (Aston *et al.,* 1981); the Ravenglass Estuary (Stanners and Aston, 1981a, b) and the Solway Firth (MacKenzie and Scott, 1982, 1993; Allan *et al.,* 1991).

A number of authors, having difficulties in matching radionuclide concentrations profiles in sediment sequences with Sellafield discharges, suggest a lag time existed between radionuclide discharge from Sellafield and deposition in nearby sediments. For example, by examining isotopic activity ratios of sediment samples and the Sellafield discharge history, Jones *et al.* (1988) determined sediment 'ages' of 1.7 years at Sellafield and 3.7 years at St. Bees, thereby suggesting a lag time of 2 years across the survey area. Stanners and Aston (1981c) and Kershaw *et al.* (1990) obtained lag times of 1.5 years and 2 years respectively for Maryport Harbour. Stanners and Aston (1981c) also determined an apparent lag of up to 4 years for the transport of sediment to the Solway Firth. MacKenzie *et al.* (1994) suggest, however, that radionuclides from any one discharge will, after mixing with older sediment, be redistributed by a continuous process so that for any particular discharge, no unique value applies for transit time from the fallout pipe to deposition. This idea is consistent with the model for Irish Sea sediment dynamics given by Dyer (1986). MacKenzie *et al.* (1994) through analysis of $^{241}Am/^{239,240}Pu$ ratios normalised to the integrated Sellafield discharge, suggest that 2-3 years may be required for complete mixing of these nuclides within the sediment pool. More recently, MacKenzie *et al.* (1998) state complete homogenisation of all Sellafield discharges occurs in the order of 1 year. This, however does not fully explain the disparity in lag times between different nuclide species.

The lag times can be explained, with reference to a simple model illustrated in Figure 2.5, by considering the inventory of radionuclides in the offshore sediment pool.

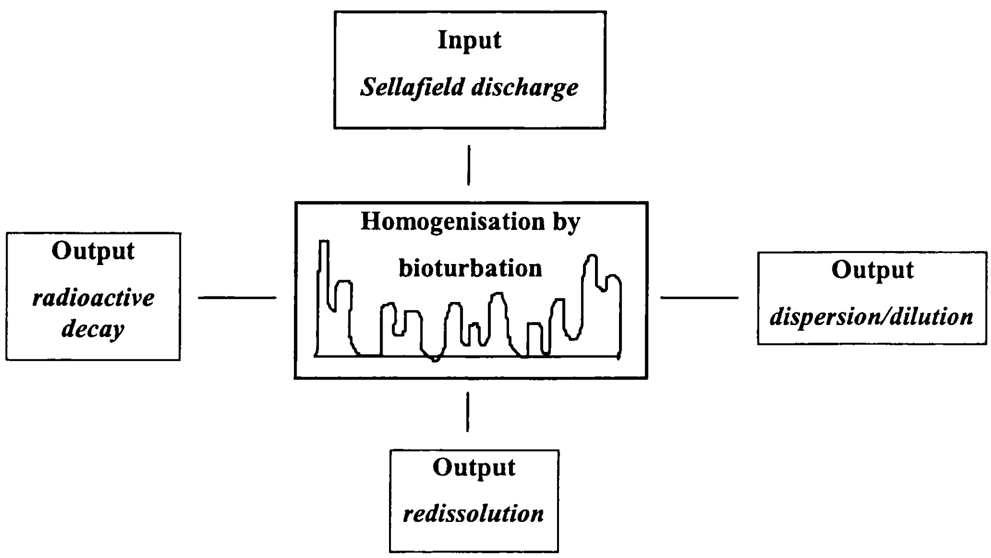

Figure 2.5 Model of radionuclide dynamics in the offshore sediment pool

MacKenzie *et al.* (1994) state that the concentration of radionuclides in the sediment pool will be determined by inputs and outputs: the input is the discharge from Sellafield over time and the outputs are radioactive decay, dispersion/dilution and dissolution. In a situation with low outputs (for example, where the half-life of the radionuclide is very long with a low rate of dispersion), the inventory of the sediment pool would, to a certain extent, follow the time integrated pattern of discharges from Sellafield. Discharges reached a maximum in the mid 1970s and have since reduced to a fraction of their peak values. Consequently, the offshore sediment pool inventory would increase rapidly, responding to the high discharges. As the discharges reduce the inventory would still increase but at a much lower rate. Where there are significant outputs, the peak inventory will occur at some point after the peak discharge. The greater the outputs, the closer the peak inventories will be, in time, to the peak discharges. The point at which peak inventories occur will vary for different radionuclides. For example, ^{137}Cs, which has a high radioactive decay rate and significant amounts of dissolution, will show peak inventories more quickly than ^{241}Am, which has a longer decay rate, little or no dissolution and ingrowth from ^{241}Pu. The output attributed to dispersion/dilution will be the same for both radionuclides because they are sorbed to the same sediment type.

Profiles of Sellafield radionuclides in accumulating intertidal sediment deposits reflect the time-integrated Sellafield discharge, rather than actual yearly discharges. In addition to this the concentrations of radionuclides in the sediment are orders of magnitude lower than effluent concentrations, indicating that there is an overall reduction in total radionuclide concentrations in the sediment as it is transported through the Irish Sea. For example, Jones *et al.* (1988) measured a reduction of ^{137}Cs concentrations over time in seabed sediments. McKay and Pattenden (1993) and Aston *et al.* (1985) note that the concentrations of actinides in seawater show an exponential decrease with increasing distance from Sellafield associated with the rapid fall in the suspended sediment concentration (the main source of actinide activity) from the coast and dilution.

The reduction in concentrations, as illustrated in the model above, has been attributed to the physical dispersion and dilution of the contaminated sediment and, redissolution of radionuclides from the sediment to seawater (Jones *et al.,* 1988, MacKenzie and Scott, 1993, MacKenzie *et al.,* 1994), the relative contribution of each, varying with nuclide species. Pulford *et al.* (1998) draw attention to work indicating that up to 75% of the ^{137}Cs initially associated with sediment within the Irish Sea sediment pool is lost through dissolution (e.g. MacKenzie *et al.,* 1994). Stanners and Aston (1982) demonstrated experimentally that 30% desorption of ^{137}Cs in seawater was possible in 10 days, but there were no such losses of ^{241}Am. Calculated losses of ^{137}Cs from suspended and transported sediments of between 54% and 59% have occurred since the mid 1970s to 1993 (MacKenzie *et al.,* 1994). Actinides may undergo some redissolution (Hunt and Kershaw, 1990), but the amount is far lower than that for ^{137}Cs because of their high K_D values. MacKenzie *et al.* (1998) state that the similarity between the average Irish Sea sediment $^{241}Am/^{239,240}Pu$ activity ratio and that of the time integrated discharge suggests that plutonium is incorporated and retained in the sediment with a similar efficiency to ^{241}Am. Thus, ^{241}Am and Pu isotopes are subject to physical dispersion/dilution, while ^{137}Cs concentrations are also reduced because of redissolution. The time taken for ^{241}Am, Plutonium and ^{137}Cs concentrations to be reduced can be expressed in terms of half-times and are calculated as 4-7 years, 4-6 and 3-4 years respectively (MacKenzie *et al.,* 1994), reflecting their known solubilities.

Whilst appreciating that transit times for individual discharge events cannot be determined because of the intense mixing which occurs in the sediment pool, studies which have invoked transit times have suggested a predominantly northerly drift of radionuclides from Sellafield. Transit times of approximately 1 year were estimated by Kershaw *et al.* (1990) for sediment deposited in Maryport Harbour, to the north of Sellafield, compared with times of 2.5 years for Newbiggin, which is closer to Sellafield, but to the south. The reason for this apparent discrepancy was attributed to a northerly displacement of radionuclides as a consequence of prevailing water movements in the Irish Sea. This was highlighted by Jones *et al.* (1988) who noted that the highest radionuclide concentrations were not associated with the areas of finest sediment, as would be expected, but instead closely mirrored water movements. Comparison of total count rate profiles of subtidal surface sediments from surveys in 1978 and 1985 along transects from Ravenglass to St. Bees Head noted a significant displacement of the peak count rate northwards by a few hundred metres.

This section has illustrated that radionuclides discharged from Sellafield undergo intense mixing before they are transported to other areas of the Irish Sea. The dominant transport process to coastal areas within the Irish, for example the Solway Firth, is via particle transport but this dominance diminishes in favour of solution transport at increasing distances from Sellafield. Subsequent to mixing, the radionuclides are subject to dispersion/dilution and, in the case of ^{137}Cs, dissolution, reducing the concentrations of radionuclides deposited in intertidal areas. The exponential nature of this decrease suggests the system is trending towards an equilibrium, meaning that any further reductions in concentration will result from long-term processes and that concentrations within the saltmarshes may remain relatively constant over extended periods. Although discharges of ^{137}Cs and ^{241}Am from Sellafield are reducing*, there will be an increase in the radionuclide inventory in areas of active sediment deposition. This will continue as long as radionuclides are supplied from the pool of sediment off the Cumbrian coast which, given the long half-lives of ^{241}Am and Plutonium, suggests this supply will continue on a timescale of 10^2-10^4 years. The predominant, but not exclusive, direction of radionuclide transport is north, mirroring prevailing marine conditions.

The following section will discuss methods for the onshore movement of radionuclides and their concentrations and behaviour subsequent to deposition.

2.5 Radionuclides in intertidal sediments

2.5.1 On-shore movement of radionuclides

It is well established that coastal areas near nuclear installations which discharge low level radioactive waste into the sea, experience contamination from both fission and activation products. Marine sediments, transported into estuaries, are subject to resuspension and aerial exposure, influencing the availability of radionuclides to biota and humans (Clifton and Hamilton, 1982). Radionuclides are transported to the coastal environment by two dominant routes: directly via tidal inundation; and, from the sea, via air, in the form of sea spray.

Contamination of the coast by radionuclides, particularly actinides, as a consequence of sea spray has been identified around a number of nuclear installations, including Sellafield, Dounreay (Caithness) and Cap de la Hague (near Cherbourg, northern France). In Cumbria there is an enhancement of $^{239,240}Pu$ and ^{241}Am activities in coastal soils above baseline levels from nuclear weapon testing fallout (Cambray and Eakins, 1980; Eakins *et al.,* 1982; Pierson, *et al.,* 1982), which diminishes with distance from the coast. The effect of sea spray deposition extends inland for some 10-17 km before becoming indistinguishable from background levels (Cambray and Eakins, 1980;

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* Some discharges have increased by an order of magnitude in recent years, e.g. ^{99}Tc and ^{14}C.

McKay and Pattenden, 1990). A similar pattern, but with far lower concentrations, has also been measured in the south-west of Scotland (McHugh and Hetherington, 1987; McKay *et al.*, 1991), although McDonald *et al.* (1992) suggest that in this area the extent of transfer is less than 1 km inland. That the enrichment is from a marine source is borne out by $^{238}Pu/^{239,240}Pu$ ratios, which are comparable with Sellafield discharge ratios and not with other sources, such as bomb fallout. The marine source of the enhancement was also suggested by Cambray and Eakins (1980) who measured a correlation between the deposition of plutonium and sodium. There appears to be no corresponding enrichment of ^{137}Cs in either Cumbria or south-west Scotland. Toole *et al.* (1990) measured a small enhancement of ^{137}Cs (values were twice that from fallout) in coastal soils in Caithness whereas enhancement of $^{239,240}Pu$ was 10 times that of fallout.

The transfer of radionuclides from sea to land occurs via mechanisms which produce an atmospheric aerosol containing marine-derived material (McKay and Pattenden, 1990). The most important of these is the bursting of bubbles at the sea surface, particularly in the surf zone as waves are breaking. It is postulated that the bubbles scavenge particulate material as they rise to the water surface although the precise mechanism is not clear. The extent of enrichment over beaches in Cumbria and south-west Scotland varies between 20 and 500 relative to the adjacent surf zone water, although continuous measurements made further inland suggest that the true value is nearer the bottom end of the range (Cambray and Eakins, 1980). The mechanism operating in Caithness is different from that above because the source of the enrichment is marine foam (spume) which accumulates in rocky inlets and contains particulate material with high levels of activation and fission products (Toole, *et al.*, 1990).

While it is important to appreciate the contribution which sea spray and spume makes to the inventory of radionuclides in the coastal zone, it must be put into perspective. Table 2.4 demonstrates that the quantity of radionuclides attributable to sea spray or spume in coastal areas is extremely small compared to the concentrations introduced from tidal waters. The observed activities are 2-3 orders of magnitude too high to be attributed to sea spray. This also has to be compared with the lesser influence of atmospheric nuclear weapons testing. McHugh and Hetherington (1987) calculated that along the Solway coast, 10 Bq m^{-2} of ^{239,240}Pu was deposited via sea spray compared to 80 Bq m^{-2} from weapons fallout. McKay *et al.* (1991) suggest that ca. 0.3-0.6% of the ^{137}Cs present in tide washed pastures in south-west Scotland is a consequence of atmospheric weapons testing fallout (see Table 2.4). Annual deposition of radionuclides from sea spray in Cumbria is considered comparable to the rate of global weapons test fallout (Chamberlain, 1996).

^{137}Cs inventories to 15 cm depth				
Region	Mean total Bq m^{-2} (%)	Weapons fallout contribution Bq m^{-2} (%)	Chernobyl contribution Bq m^{-2} (%)	Sellafield contribution Bq m^{-2} (%)
Cree	54000 (100)	3170 (0.58)	8435 (1.56)	528395 (97.8)
Dee	442500 (100)	2685 (0.6)	5415 (1.22)	434400 (98.2)
Fleet	468000 (100)	2130 (0.45)	5710 (1.22)	459960 (98.3)
Nith	622500 (100)	2220 (0.35)	7900 (1.27)	612380 (98.4)
Urr	95100 (100)	2990 (0.31)	6885 (0.72)	941125 (99)

Table 2.4 Contributions of differing components to total tide-wash pasture (taken from McKay *et al.*, 1991)

2.5.2 Spatial distribution of radionuclides in intertidal sediments

The dominant transfer therefore of Sellafield-derived radionuclides to intertidal zones in the Irish Sea is due to sediment (to which radionuclides are sorbed) being transported by tidal waters and deposited during the inundation of intertidal flats and saltmarshes. The highest activities of Sellafield derived radionuclides in intertidal areas in Cumbria occur where there is direct tidal inundation of the coast (Livens and Baxter, 1988). The significance of this source of radionuclides has been demonstrated in the Solway Firth by McDonald *et al.* (1992) who observed that levels of both ^{137}Cs and ^{241}Am in areas flooded by tidal waters were generally over 25% of the generalised derived limits (GDLs) published by the NRPB*, making them worthy of further radiological investigation. Of equal importance is the fact that, while concentrations of radionuclides within intertidal sediments may not be very high compared to total discharges, the volume of sediments involved in many west coast estuaries, such as the Solway Firth, means that total radionuclide inventories are very high (Kershaw, 1993). With continued infilling of estuaries, these inventories will increase, despite the reduced discharges from Sellafield.

Radionuclide distributions within intertidal sediments have been investigated in many studies but little attention has been paid to integrating the radiological aspects with geomorphological considerations. General patterns of radionuclide distributions are evident but these cannot be modelled or even fully understood without an understanding of their geomorphological context. Within the Irish Sea sub-tidal and intertidal sediment system, there is a positive correlation between mud content and actinide activity (e.g. Aston *et al.,* 1985). Aston and Stanners (1981) found that the highest concentrations of ^{241}Am occurred in the inner sections of the Ravenglass Estuary which is subject to low flow conditions during the ebb tide. Aston and Stanners (1982 a, b) showed a clear correlation between the activity of ^{137}Cs and the silt content of sediments. Jones *et al.* (1984) using a hovercraft to survey the Solway Firth, determined that the highest concentrations of ^{137}Cs were found in coastal embayments, protected from strong tidal channels. High concentrations were also found near the mudflat/saltmarsh boundary, near the mean high water mark. The differentiation between tidal flat and saltmarsh sediments was also noted by Horrill (1983) in the Esk Estuary where radionuclide concentrations on marshes were two or three times those of intertidal silts. Enrichment

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* The Generalised derived limit is published by the National Radiological Protection Board. It was recommended by the NRPB that in areas where measured radionuclide values exceed 25% of the GDL (for the appropriate environment, e.g. well mixed soil, marine) the critical group doses for that area should be examined more closely. Generalised derived limits are determined by consideration of the exposure of a critical group in an exposed population. GDLs provide a convenient reference level against which to compare results for monitoring (MacKenzie *et al.,* 1996)

of ^{241}Am and ^{137}Cs concentrations on saltmarshes in Ravenglass was also identified by Aston and Stanners (1981, 1982a) where fine-grained sediment is trapped by vegetation leading to deposition in the late stages of the tidal cycle. In the Solway Firth there is also a easterly decrease in radionuclide concentrations which is evident even if the effect of sediment size is statistically removed (Garland *et al.*, 1988; Allan, 1993) which may be attributed to increasing distance from Sellafield.

The considerable spatial variation in the distribution of radionuclides in estuaries has implications for environmental monitoring. This difficulty was highlighted by Aston and Stanners (1982b) whose mean measurements of a number of radionuclides in the Ravenglass estuary were consistently higher than the corresponding monitoring data reported by MAFF. While this was seen as a criticism by Aston and Stanners (1982b) of the site chosen by MAFF for their monitoring, Hemingway (1982) argued that, because the sample taken by Aston and Stanners nearest the MAFF site at Newbiggin was near to the mean value calculated for the whole estuary, the site at Newbiggin was therefore representative of mean radionuclide concentrations. However, mean concentrations are as important from a radiological point of view as peak concentrations. In order to improve the strategy for selection of monitoring sites, an understanding of saltmarshes in relation to the deposition of radionuclides is necessary.

2.5.3 Deposition of radionuclides in intertidal areas

The deposition of sediment in intertidal areas has already been investigated from a saltmarsh perspective (sections 2.2.2 and 2.2.3) where it was shown that while tidal inundation can be a strong control over intertidal sedimentation, other factors such as vegetation and storms also have important roles. It has already been demonstrated that both ^{137}Cs and ^{241}Am are adsorbed preferentially on to fine grained particles so it is not surprising that the highest radionuclide concentrations are associated with fine grain sediment accumulation. It must however be determined which method of deposition will result in the highest radionuclide concentrations: tidal inundation, vegetation induced or storm action.

Given that contaminated sediment is carried shorewards by tidal waters, it is logical to assume that the dominant control over the distribution of the sediment, and therefore radionuclides, will be tidal action. The importance of tidal inundation has often been alluded to. Hutchinson (1994) and Hutchinson and Prandle (1994), comparing marshes of different ages in the Dee Estuary, showed that the highest ^{137}Cs inventories were contained in the youngest marsh subject to frequent tidal inundation. The wide range of inventories measured, however, (e.g. 146 kBq m^2 - 1258 kBq m^2) on this marsh indicates that the pattern of deposition is not simple. Horrill (1984) noted that the spatial variability on an ungrazed marsh was controlled by tidal immersion and that areas of the marsh covered most frequently by the tide (the marsh edge) had the highest inventories. An inverse relationship therefore exists between inventories of radionuclides and height above ordnance datum (McKay *et al.,* 1991; Horrill, 1983). The highest radionuclide concentrations measured by McKay *et al.* (1991) in saltmarshes next to the River Cree (Solway Firth) were found in the centre of the marsh, associated with hollows which trap tidal water thereby increasing the duration of inundation and creating low energy conditions in which fine suspended sediment can settle. This pattern was also recorded by Walling and Bradley (1988), demonstrating the importance of micro-topography on marsh radionuclide levels. While the tidal influence on radionuclide deposition is clearly important, the retention of tidal waters by either topographic irregularities or vegetation, and the resultant deposition of fine sediment appear as important as the frequency or duration of inundation.

Horrill (1983) presents a more complex picture, indicating that height above ordnance datum is not the only factor involved in the spatial pattern of radionuclides. The highest concentrations of ^{241}Am in the marshes investigated (Esk Estuary) were found in the strandline which, being the highest point on the marsh, is subject to the least tidal inundation. It is suggested that the high concentrations are as a result of fine sediment being pushed towards the strandline by river currents opposing the silt-laden tidal waters. This seems unlikely except in situations of extreme river flow. A more plausible explanation may be the existence of a creek in the centre of the area (indicated on Horrill's maps) supplying very fine sediment to the rear parts of the marsh during high spring floods, again stressing the influence of topographic features on radionuclide distributions.

The influence of vegetation has also been considered by some authors. The importance of vegetation, in particular, *Spartina anglica,* was investigated by Oldfield *et al.* (1993) who suggested that the structure of the plant facilitated the trapping of silt and was therefore responsible for elevated levels of ^{137}Cs and ^{241}Am present in saltmarshes compared to intertidal flats. Horrill (1983) noted that while much of the spatial variability of actinide concentrations could be attributed to tidal inundation, the type of vegetation present on the marsh also played an important role in delineating the highest concentrations of radionuclides. Again, it was suggested that the structure of different marsh species resulted in different sediment trapping capabilities. Horrill (1984), in a comparison of grazed and ungrazed marshes, showed that the spatial variability of radionuclide concentrations on the grazed marshes were a function of the tide only, whereas on the ungrazed marsh, vegetation played a key role. The structure of the uncropped vegetation was able to trap sediment more efficiently. It is, however, difficult to determine which of these two parameters, vegetation or tides, has the dominant control since, ultimately, the type of vegetation present on a particular part of the marsh will be determined by hydroperiod. While this example may not fully elucidate the importance of vegetation, it does demonstrate the importance of landuse in influencing the processes that control the deposition of radionuclides.

2.5.4 Radionuclide profiles in accumulating sediment

As well as spatial variations in the deposition of radionuclides, consideration of temporal variation in deposition rates is important. Within accreting sedimentary environments, such as saltmarshes, a time-integrated profile of Sellafield discharges can be recorded (e.g. Aston and Stanners, 1979; Stanners and Aston, 1981a; MacKenzie and Scott, 1982; Allan *et al.,* 1991; Allan, 1993; MacKenzie *et al.,* 1994). The depth at which the peak activity occurs demonstrates the sediment accretion which has occurred since the peak activities in the Irish Sea occurred. The deeper the peak, the more sediment has been accreted over time. MacKenzie and Scott (1982) measured sedimentation rates of between 2.5 and 3 cm y^{-1} in the Solway Firth. The range of rates measured by Stanners and Aston (1981a) for the Ravenglass estuary were between 0.25 and 71 mm yr^{-1}. If no peak occurs, it can be assumed that sediment accretion is not the dominant physical process occurring on the marsh. Clifton and Hamilton (1982) suggest that three types of profile may be evident:

- containing a continuous record of the Sellafield discharge
- only representing recent, low level radionuclide inputs
- older sediments which do not reflect any significant inputs as a result of erosion of surface sediments.

Comparison of a number of cores from the same marsh can illustrate the development history of that marsh (Hutchinson and Prandle, 1994).

Qualitatively, the peak activity found in the profile, can be equated to the time-integrated peak discharges from Sellafield in the mid-1970s and this can be used as a dating tool. Direct comparison between the profile radionuclide concentrations and the annual discharges from Sellafield cannot be done because these two values are not linearly related. There is an inherent weakness in using a comparison of the two profiles to establish a chronology because of probable variations in the accumulation rate of the marsh. Of more use to sedimentological studies, is the comparison of activity ratios of different radionuclides. Activity ratios can be directly compared with those of the time integrated discharge. MacKenzie and Scott (1993) demonstrated that the $^{241}Am/^{239,240}Pu$ ratio at different depths of a sediment core from the Solway was (within error) equal to that of the time-integrated discharge appropriate to the year of deposition. Aston and Stanners (1979) suggest that the most reliable way of determining an acceptable sedimentation rate is the use of the ratio of two radionuclides of the same element, for example $^{134}Cs/^{137}Cs$, because the isotopes will behave the same way in different chemical environments. Clifton and Hamilton (1982) used ^{137}Cs and ^{241}Am suggesting that once associated with sediment, these radionuclides also behave similarly and their long respective half lives reduce any uncertainties arising from radioactive decay occurring over long time periods.

Radionuclide activity ratios in the sediment profile can also be used to determine the relative age of sediments. Sediments which have been deposited, via particulate transport, would be expected to have radionuclide activity ratios that are a constant fraction of the time-integrated Sellafield discharge. MacKenzie *et al.* (1994), however, noted a systematic decrease in the $^{137}Cs/^{241}Am$ activity ratio found in sediments relative to the time-integrated discharge since the late 1970s. This implies a loss of ^{137}Cs relative to ^{241}Am from the pool of sediment supplying these intertidal areas over time. This loss has come about in two ways: dissolution of ^{137}Cs during transport from the sediment pool to the deposition site; and to a lesser extent, decay of ^{137}Cs relative to ^{241}Am. There will also be an increase in the concentration of ^{241}Am because of the ingrowth from the decay of ^{241}Pu. This reduction in the ratio over time means that higher $^{137}Cs/^{241}Am$ ratios can be interpreted as indicating older sediment.

The use of vertical profiles of radionuclides in saltmarsh sediments must, however, be performed with care. Analysis of the peak depths must be put into a geomorphological context before interpretation. Tidal, vegetational and landuse characteristics of the marsh, as well as its development history all influence the peak depth yet few authors have attempted this kind of study. Carr and Blackley (1986) state that radionuclide patterns recorded in the sediment can only be used if it is shown that there has been no movement of the radionuclides subsequent to deposition and no post-depositional mixing of the sediment.

Determining whether there is movement of radionuclides subsequent to deposition is important in terms of using the radionuclide profiles for geomorphological purposes but it is also important from a radiological point of view. Exposure of people who use coastal areas for work or recreation will come from two sources: external exposure from gamma-emitting radionuclides; and, internal exposure from alpha- and beta-emitting radionuclides. Approximately 90% of the total dose resulting from contamination of tidally inundated land in the south-west of Scotland comes from external exposure to radiation from ^{137}Cs, with the remaining 10% from the inhalation and ingestion of

^{241}Am and ^{239,240}Pu (McKay *et al.,* 1993). The critical group* in the Solway Firth are farmers who graze cattle on the saltmarshes. The most contaminated sediment in saltmarshes have been shown to represent peak discharges from the 1970s and these peaks are often buried within the sediment profile. Although the mean range of ^{137}Cs gamma-rays in soils is >>1 cm (McKay *et al.,* 1993), these high activities do not usually contribute to the dose received by the public. If, however, the sediments containing high radionuclide concentrations are somehow returned to tidal waters or to the saltmarsh surface, they will increase the total dose received by critical groups. MacKenzie and Scott (1993) observe that in lower energy sites such as saltmarshes, burial is effective in reducing external exposure but that this may not be the case in environments where buried sediments containing radionuclides are subject to erosion, resuspension and redistribution. The mechanisms for possible movement of radionuclides in saltmarshes will now be considered.

2.5.5 Radionuclide mobility within accumulating sediments and redistribution within the marine environment

Hetherington and Harvey (1978) said that the ultimate question, when considering the affinity of radionuclides for sediment, is "..does the sediment act as a final sink or as a temporary reservoir?" This same question can be asked of saltmarshes. Are *they* a permanent store for sediment, and thus radionuclides, or simply a transient depository? In order to answer both of these questions, the chemical behaviour of radionuclides within saltmarshes must be considered as well as the physical behaviour of the saltmarshes as a whole (Livens and Baxter, 1988). The former will be discussed first, although it is important to realise that the chemical and physical aspects of the environment in which the radionuclides are deposited should not be treated in isolation.

In section 2.4.3 the nature of the geochemical associations of ^{137}Cs and ^{241}Am with respect to Irish Sea sediments was introduced. It was shown that while the majority of

* The critical group comprise members of the public who are most highly exposed to a source of radiation.

^{137}Cs released from Sellafield remains in solution, a fraction becomes associated with illite clays. Most of the ^{241}Am and Pu discharged rapidly becomes associated with fine sediments. The K_D value for Cs in Irish Sea water is 10^3 and the value for Am and Pu (III,IV) is 10^6 (Kershaw *et al,* 1992). The nature of radionuclide associations is dependent on the surrounding chemical conditions. In the Irish Sea, the environment is highly saline, alkaline and well oxygenated. In saltmarsh sediments, however, the environment can be of a lower salinity, with a pH ranging from alkaline in areas experiencing tidal inundation to acidic in organic rich sediments (such as those at the landward edge of the marsh) and reducing conditions occur in some circumstances. This chemical change may have an important bearing on the associations of the radionuclides (Allan *et al.,* 1991).

Within the Irish Sea, fine-grained sediment, including that found on saltmarshes, has a ^{137}Cs K_D value of 10^5 (Pulford, *et al.,* 1998) which is higher than values calculated for Irish Sea sediments and the Firth of Clyde (Baxter *et al.,* 1979, Stanners and Aston, 1982, McCartney *et al.,* 1994). Sequential leaching experiments showed that 98% of the ^{137}Cs was associated with the residual phase of Solway Firth intertidal sediments. This, and the small amount of ^{137}Cs removed by mild leaching reagents, indicates there is a very low degree of potential mobility within the sediment. This also means that biological uptake will be very small. Turner *et al.* (1994) treated sediments from the upper Dee Estuary with acetic acid which failed to remove any sorbed ^{137}Cs ions, indicating, they suggest, an irreversible reaction of ^{137}Cs with sediments. The higher K_D value of ^{137}Cs in the upper part of the Dee estuary was attributed by Turner *et al.* (1994) to there being less competing sorbable ions as a result of the reduced salinity of the water.

This suggestion is given some credence by Cundy and Croudance (1995) who suggest that the degree of collapse which occurs within an illite lattice, trapping any ^{137}Cs ions, depends on the ionic composition of the surroundings. In fresh water, the incidence of ^{137}Cs alone is insufficient to induce lattice collapse but in a higher concentration of K^+ ions, interlayer collapse occurs and the ^{137}Cs is irreversibly adsorbed. In marine waters, the conservative nature of ^{137}Cs is attributed to high concentrations of K^+ inducing lattice collapse leaving only exchangeable sites for adsorption of ^{137}Cs. It is therefore the coincidence of illites which have not been subject to lattice collapse and a reduced K^+ concentration which allows the ^{137}Cs ions access to the interlayer exchange sites, where they are subsequently trapped.

Investigations by Pulford *et al.* (1998) showed a reduction in the percentage of residual phase ^{137}Cs from 98% in intertidal sediments to 80-85% in saltmarsh sediments because of either changes in the geochemical conditions during on-shore transport or particle size sorting of the sediments. Further inland the residual fraction increased again to 98-99% which was attributed to either a reduced hydroperiod, leaching by freshwater, finer particle size, presence of vegetation or a steeper salinity gradient. If any of these were responsible for the high percentage of ^{137}Cs in the residual phase, a progressive decrease in the fraction would be expected with the lowest amount in the intertidal mud. This area, however, is subject to the highest amount of tidal inundation, has the greatest sediment size, little freshwater leaching, no vegetation and a reduced salinity gradient, suggesting that other complexities are involved.

This example demonstrates that the situation resulting from a change of chemical environments is complicated, but it also shows that once ^{137}Cs enters the intertidal flat and saltmarsh environment, it is tightly bound to clay material and only a small fraction is mobilised (Allan, 1993). Livens and Baxter (1988) suggest that ^{137}Cs association with the residual phase means that thereafter only physical processes are important in its transport.

Studies of the association of actinides have concentrated on Pu isotopes rather than ^{241}Am, but in general, it has been shown that the actinides are associated, predominantly, with the Fe/Mn oxide/hydroxide phase and the organic phase (Assinder, 1983, Livens and Baxter, 1988; Allan *et al.,* 1991; Pulford *et al.,* 1998). The Fe/Mn oxide/hydroxide phase can be dissolved under reducing conditions and the organic phase is broken down by biological processes, meaning that that Pu has greater potential mobility or bioavailability than ^{137}Cs. In some estuaries, there has been more Pu in the water leaving the estuary than in incoming waters as a result of remobilization from sediments (Kelly *et al.,* 1991). Hamilton-Taylor, *et al.* (1987) noted enhanced remobilization of Pu (III and IV) at low salinities but offered no real explanation as to why this should occur.

Within the Solway (Cree estuary), remobilization of $^{239,240}Pu$ did not occur in significant quantities because the salinity did not drop sufficiently, although Garland *et al.* (1988) suggested that the requisite salinity (< 4 $^{0}/_{00}$) may occur if there was a sufficient influx of fresh water, for example, during a flood. Pulford *et al.,* (1998) noted that, in sediments from Southwick Merse in the Solway, there was no obvious Fe or Mn dissolution with depth and that even though there was some breakdown of organic matter, any Pu released was rapidly re-adsorbed by other components. These studies again suggest, that once Pu and ^{241}Am are deposited in intertidal sediments they will not be significantly remobilised due to chemical changes in the environment.

While there is no apparent movement of radionuclides due to chemical processes in estuaries, there may be physical transport. In the Tamar estuary, Clifton *et al.,* (1995) determined that physical mixing by bioturbation, rather than accretion, was responsible for sediment depth profiles of contaminants. Alternatively, Aston and Stanners (1979), using $^{134}Cs/^{137}Cs$ activity ratios, determined that in the Esk estuary, radionuclide profiles resulted from the sedimentation of contaminated particles and that there was little influence from any post-depositional modifications. Oldfield *et al.* (1993) noted that cores in a number of saltmarshes and mudflats high in the intertidal zone, provided consistent records of the deposition and storage of Sellafield discharge. In contrast, MacKenzie and Scott (1993) observed large and irregular temporal variations in the vertical profiles of ^{137}Cs in intertidal beach sediments which were not related to concomitant Sellafield discharges, suggesting the sediments were subject to alternating periods of erosion and accretion. High energy environments will result in sediments being subject to repeated resuspension in contrast to low energy environments which will facilitate accretion. It is clear that different areas will be subject to varying amounts of disruption as a result of either bioturbation and/or high energy conditions, resulting in the vertical profile of radionuclides being disturbed.

Saltmarshes do accrete sediment and can therefore bury high radionuclide activities but, as shown in some detail in Section 2.2.6, they can also erode. This means that older, more contaminated sediments can be reintroduced into the estuary, transported and redeposited, thereby increasing the activity of surface sediments. Garland *et al.,* (1988) noted that while the Solway is being in-filled by sediments from the Irish sea there is also a redistribution of sediment from eroding saltmarshes and cliffs. This means that sediments of different ages will be deposited contemporaneously on active areas of accretion, potentially confusing the picture with regards to the deposition of radionuclides. The extent of mixing or its radiological implications have not been determined in the current literature.

This section has shown that radionuclides can be used in sedimentological studies by examination of their surface distributions and depth profiles. It has also been shown that the pattern of radionuclide deposition is profoundly influenced by the nature of the sediments with which they are associated. Information concerning the source, movement and behaviour of radionuclides to and within intertidal areas is essential if radionuclide concentrations found in these areas are to be accurately interpreted. MacKenzie and Scott (1993) write that "...in order to derive a predictive model for external exposure resulting from contamination of intertidal areas, it is necessary to characterise both the radionuclide supply mechanism and the processes affecting the sediment at the site of deposition". In order to derive a predictive model for saltmarsh development using radionuclide contamination of saltmarsh areas, a similar characterisation of radionuclides and sediment is required.

2.6 Research Aims

This chapter has concentrated on two main themes: the sedimentological processes driving the establishment and development of saltmarshes and the contamination of saltmarshes, particularly those in the Solway Firth, by anthropogenic radionuclides, specifically from the Sellafield Nuclear Fuel Reprocessing Plant.

The study of radionuclides in the intertidal environment can be a valuable tool in investigating the geomorphology of saltmarshes. Also, the knowledge of geomorphological processes within this environment is essential in understanding the distribution of radionuclides. A primary objective of this work is to evaluate the role of geomorphological processes in the construction of contemporary distributions of contaminant radionuclides and to identify those processes which are of importance with respect to determining future trends in radionuclide concentrations and distributions.

The review of literature in this chapter has highlighted a number of areas which require further investigation, some of which will be addressed in this work.

Firstly, few studies have investigated the influence of physiographic location on saltmarsh development. Stevenson *et al.* (1988) note that such an analysis is difficult because marshes located in different physical settings will be geomorphologically distinct. It was highlighted however, that the dominant control of marsh development, especially in a macrotidal system, is the hydroperiod. Within the Solway there are a number of different marshes, located in different physical settings but their close proximity, means they are subject to similar (not identical) tidal conditions. This means that the Solway is an ideal location for such an investigation.

Aim 1: to investigate the influence of physiographic location on saltmarsh development.

Secondly, it was highlighted that in the investigation of sedimentation rates on saltmarshes, studies often concentrate on one method, determining the changes in a marsh over a particular timescale, e.g. artificial markers such as coal dust may be introduced to a saltmarsh to investigate rates over a ten year period or less; historical rates can be determined using markers such as ^{137}Cs from nuclear weapons testing. Few studies have integrated the use of different methods operating over different timescales. This is important given the time dependent nature of saltmarsh development, especially in macrotidal systems (French *et al.,* 1995b). Within the Solway there exists a suitable marker horizon from the radioactive discharge from Sellafield which, if integrated with a study of contemporary rates, could give a detailed account of recent marsh development in the Solway Firth. If successful this type of integration could be an important methodological tool in saltmarsh studies.

Associated with this investigation is the opportunity to establish how the Solway saltmarshes agree, or otherwise, with established literature on the patterns of saltmarsh sedimentation. The Solway Firth has been neglected in saltmarsh studies and this work aims to redress this. An important aspect of this study is to determine the effect of different vegetation species on allochthonous and autochthonous sedimentation in Solway Firth saltmarshes. There exist in the Solway two dominant pioneer vegetation species: *Puccinellia maritima* and *Spartina* sp., thereby providing an opportunity to determine how marshes, with similar physical conditions (tide, sediment supply and sediment type) respond to different vegetation types. This study will allow an assessment of the importance of vegetation in promoting sediment deposition in saltmarshes.

Aim 2: to integrate the use of different methods utilising different timescales, to establish sedimentation rates and patterns in the Solway saltmarshes, and to identify the geomorphological factors responsible for those rates and patterns, in context of varying vegetation species.

The above aims are directed specifically at deficits in saltmarsh literature but an important part of studying marshes in the Solway Firth is the contamination of these by radioactive discharges from Sellafield. Understanding of contamination patterns necessitates that the physical conditions of the deposition site are also understood, an aspect of radionuclide studies which has been neglected. The corollary to this is that the pattern of radionuclide distributions within a saltmarsh can facilitate the investigation of that saltmarsh.

Aim 3: to determine the influence of physical conditions on a saltmarsh (tidal influence, vegetation, sediment size, organic content) in understanding radionuclide distribution patterns and concentrations.

Aim 4: to use the pattern of radionuclide distributions and concentrations as a tool to investigate saltmarsh development processes.

Further to this is the fact that if the pattern of saltmarsh change can be determined, then the future of the radionuclides can be determined. The literature shows that within an accreting sediment the high radionuclide activities which were discharged from Sellafield during the 1970s will be buried and will therefore cease to pose a potential threat to critical groups occupying coastal environments. Saltmarshes, however, are dynamic systems and this has to be taken into account when trying to predict the future influence of high radionuclide concentrations.

Aim 5: to explore the extent to which post depositional processes affects the subsequent distribution and concentration of ^{137}Cs *and* ^{241}Am *in a saltmarsh system.*

The above aims will be addressed in the following chapters.

3. PRELIMINARY INVESTIGATIONS

3.1 The Solway Firth

3.1.1 Physical setting

The Solway Firth is located on the west coast of Britain and forms part of the border between Scotland and England. With a coastline of roughly 300 km from the western extent of Luce Bay in Dumfries and Galloway to Whitehaven in Cumbria, it is one of the largest estuarine embayments of the Irish Sea.

The Solway lies in a deep sedimentary basin of Caledonide age (Skipsey, 1988), trending east-west and bounded to the north and south by the Southern Uplands and Lake District, respectively. The northern shore of the Solway is dominated in the west by the Criffel granite and by a strip of Silurian greywackes resulting in a craggy and broken coast (Steers, 1973). East of the River Nith, to the head of the Firth, the character of the coast changes, becoming low-lying with isolated exposures of Permian and Triassic sediments.

The present coastal configuration has been shaped by successive marine transgressions and regressions as a consequence of glacial activity during the Quaternary. 18 000 years before present (years BP), during the last glacial maximum, global sea levels were around 130 m below Ordnance Datum (O.D.), and although sea levels west of the present Scottish mainland were much higher because of ice loading on the land (Jardine, 1977), this resulted in a lack of marine sedimentation in the Solway (Black *et al.,* 1994). By the beginning of the Holocene (10 000 years B. P.) sea levels were higher and extended 7 km north of the present head of Wigtown Bay, occupying many of the coastal inlets between Wigtown and Dumfries and probably occupying Lochar Gulf, an embayment south-east of Dumfries (Jardine, 1975). Transgression of the sea into the inner Solway began around 8100* years B. P. and ended 5600* years B.P, with the

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* Dates established by radiocarbon dating, using the Libby half-life for radiocarbon, 5568 ± 30 years (Jardine, 1975)

transgression ending in the western Solway around 5000* years B. P. Evidence for the transgression has come largely from carbon dating of the stratigraphic record, however a number of physical features also indicate a marine incursion into the estuary. In the west of the Firth, the sea cut into the greywackes and Criffel granite producing features such as sea cliffs, arches and stacks which are now positioned well inland of the current coast. In the low-lying east, carselands, which are analogous to the intertidal flats and saltmarsh environments which currently occupy the fringes of the Solway, can be identified covering extensive areas landward of the present coast. The subsequent fall in relative sea levels, which has occurred steadily to the present day, led to such carseland being abandoned by the sea and elevated by uplift to a present altitude of between 8 m and 10 m O. D. (Jardine, 1975)

The difference in physical character between the west and east of the Firth has resulted in these areas being considered as different entities. Indeed, of the few Solway studies which have occurred, most have concentrated on the inner Firth (for example, Marshall, 1962; Rowe, 1978; Black *et al.,* 1994), which can be defined as the area east of a line from Southerness Point to Dubmill Point. Perkins (1978) noted that the Solway should be regarded as a complete unit because of the unity of the physical and biological conditions within it, although he also identified a number of sub-units within the Firth emphasising its complexity.

Figure 3.1 illustrates a number of definitions which have been used to identify the Solway. For the purposes of this work the line from Burrow Head to St. Bees Head will be used for two reasons. Firstly, Perkins (1978) suggests that Luce Bay is the sub-unit which has the weakest link to the estuary as a whole. Secondly, MacKenzie *et al.* (1987) identified Burrow Head as the boundary between different modes of radionuclide transport: particulate transport dominating east of the headland; and, a mixture of particulate and solution transport to the west.

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* Dates established by radiocarbon dating, using the Libby half-life for radiocarbon, 5568 ± 30 years (Jardine, 1975).

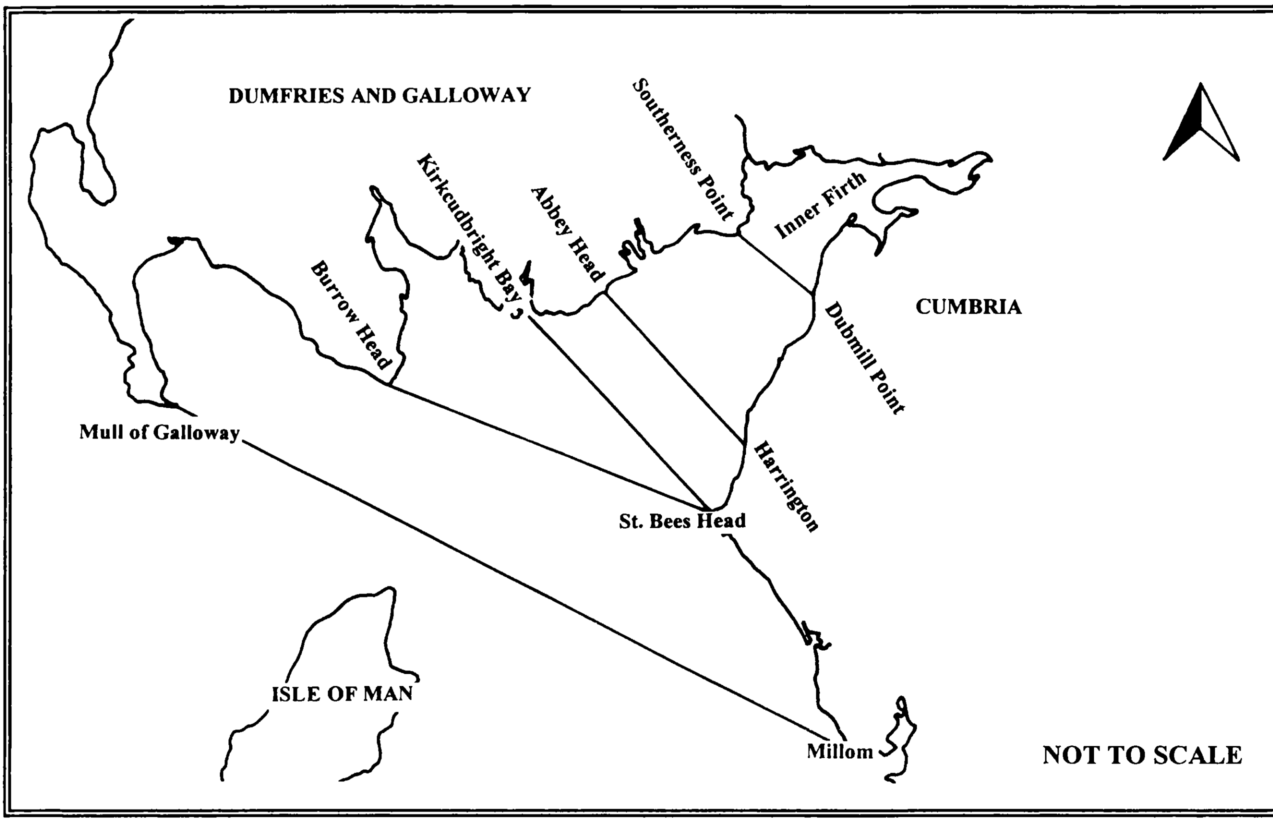

Figure 3.1 Definitions of the Solway Firth (Perkins, 1978)

3.1.2 Hydrology

There are three factors which must be considered with regard to the hydrology of the Solway: the effect of tides, waves and fluvial input. The mean tidal range in the Solway is 8.4 m (Black, *et al.* 1994) therefore the estuary can be described as macro-tidal (Davies, 1964). It is a Type 3, well mixed estuary (Dyer, 1972), which means there is no vertical stratification between the fresh fluvial input and the saline marine waters.

The flood and ebb tides at Hestan Islet (Admiralty tidal constant) are symmetrical but once the tidal waters enter the funnel-shaped part of the estuary they are progressively distorted in the following ways (Figure 3.2):

- the flood tide exceeds the ebb by around 0.77 ms^{-1}. (Perkins, 1966)

- during spring tides, the ebb, at the head of the estuary, drains the flats and marshes very slowly, lasting 6 hours with a 5 hour slack period. The flood tide however, rises over 4 metres in 2 hours
- the tidal amplitude is enhanced by the shape of the Firth, as illustrated in Table 3.1

	Silloth	River Annan	Glasson
Spring tide range (1966)	8.4 m	7.1 m	5.2 m
Spring tide range (1991)	8.2 m	7.7 m	5.5 m

Table 3.1 Mean spring tidal ranges (table from Black *et al.,* 1994)

- the narrowing of the estuary means that the height of the highest astronomical tide at Redkirk near the head of the estuary is 0.85 m higher than the Highest Astronomical Tide (HAT) in the middle of the estuary (Black *et al.,* 1994)
- the time of the peak and trough elevations at Hestan Islet precedes those at the head of the estuary (Gurbutt, 1993).

The shape of the estuary also accommodates the development of a tidal bore. Babtie *et al.* (1966) observed a tidal bore entering the Solway on a number of occasions, measuring on average 0.6 m in height (exceptionally 1.5 m), at an average speed of 4.0m s^{-1}.

The Solway coast is also influenced by wave action, although the enclosed nature of the Firth makes this of lesser importance than tides. The height and direction of waves is largely dependent on prevailing south-westerly wind conditions (Black *et al.,* 1994). Records for the outer Solway indicate that significant wave heights of 1.5 m are exceeded 10% of the year, while heights of 0.5 m are exceeded 75% of the year (Black *et al.,* 1994).

Coastal areas most vulnerable to wave action are those on the northern shore, particularly east of the River Nith which are affected by waves over the longest fetch. Although waves from the outer firth are refracted into the inner firth, the most significant waves are those generated within the confined reaches of the Solway. Indeed, Black *et al.* (1994) suggest that local storminess, producing successive waves with short wavelengths, may be more important to local erosion of the inner Solway.

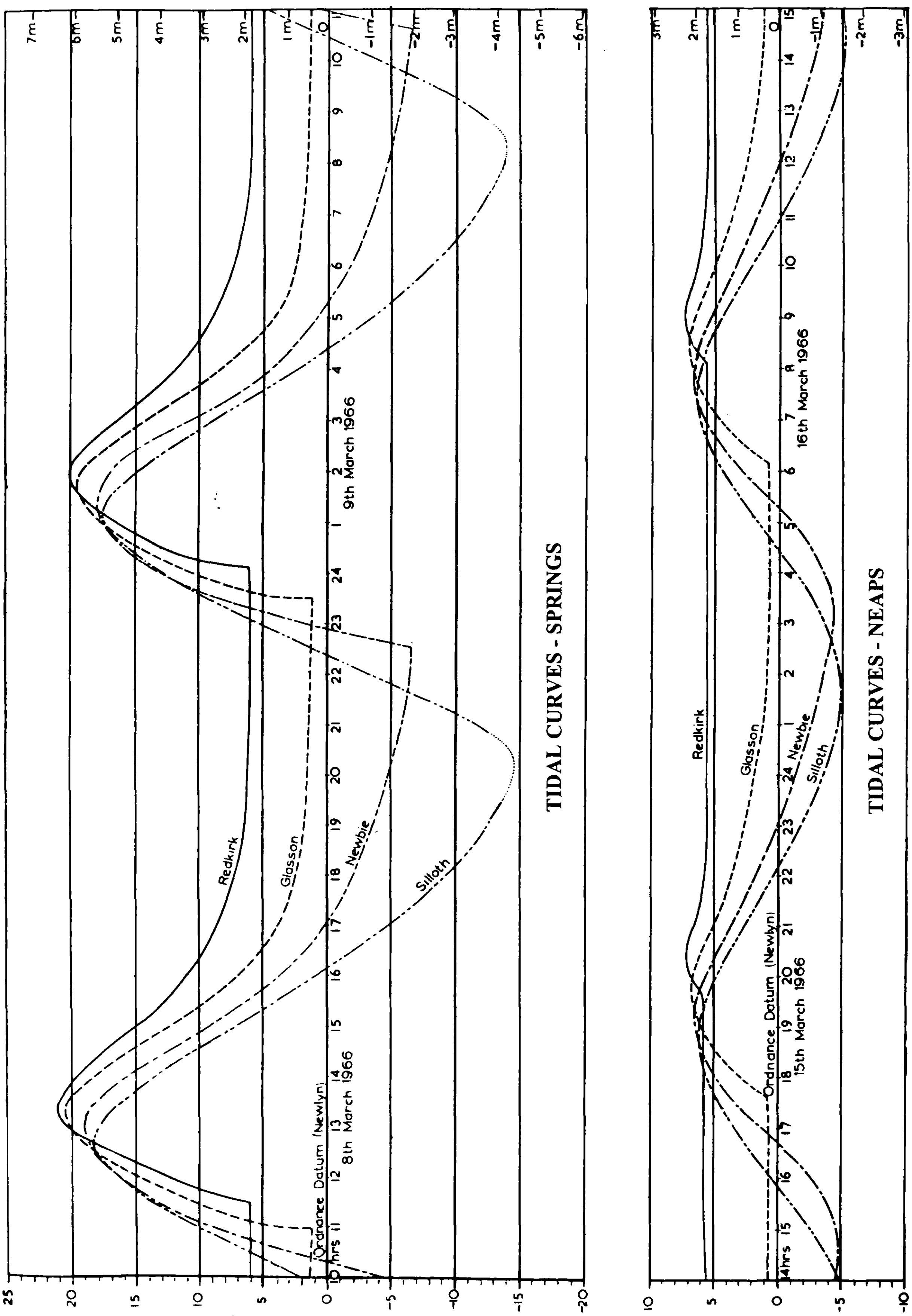

Figure 3.2 Tidal Curves of the Solway (Babtie, *et al.*, 1966)

There are eight main rivers which flow into the inner Solway, none of which has a large flow, as demonstrated in Table 3.2. Data are unavailable for the Rivers Cree and Fleet which enter the outer Firth area but these rivers are smaller than the Nith.

River	Urr	Nith	Lochar	Annan	Esk	Eden	Wampool	Waver
Flow m^3s^{-1}	5	40	5	28	34	45	2	3

Table 3.2 Average flows for rivers entering the inner Firth (Gurbutt, 1993)

3.1.3 Sediment characteristics of, and movement within, the Solway Firth

Sediments in the Solway are considered by many authors to be sandy (e.g. Marshall, 1960-61; 1962; Perkins, 1966; Allen, 1989). Typical sediment analyses by Marshall (1962) and the Solway River Purification Board (1993[*], 1995[†]) for corresponding sites are given in Table 3.3. Babtie *et al.* (1966) note a typical analysis of the Solway sediment is: 2%, 0.25 - 0.125 mm; 70%, 0.125 - 0.0625 mm; 28%, < 0.0625 mm.

Although the general characteristics are similar, it is clear that there are significant differences in measurements taken from the same site between different survey years. These mean results also hide differences in distribution of different sediment sizes. In general the finest material is located in the innermost areas of bays and estuaries (Perkins, 1966) and the coarsest sediments are found adjacent to, or in, tidal channels (Perkins and Williams, 1965).

[*] Data for the survey in 1993 were obtained attained by personal communication with the Solway River Purification Board, now part of the Scottish Environmental Protection Agency (SEPA).

[†] Rendall and Bell, 1995.

	Percentage in each size fraction								
	Coarse sand*	< 0.125 mm!		Fine sand*	0.125 - 0.063 mm!		Silt and clay*	< 0.063 mm!	
Sites	1962	1993	1995	1962	1993	1995	1962	1993	1995
Powfoot	8.7	4.51	45.05	88.4	62.01	46.09	2.9	34.59	8.86
	-	5.77	1.54	-	50.31	68.24	-	45.12	30.24
Kennethbank	0.8	42.15	0.84	95.4	54.61	85.83	3.8	7.34	13.33
	0.4	-	1.15	92.7	-	84.06	6.9	-	14.80

* Terminology used by Marshall (1962)

! Figures used by Solway River Purification Board (1993, 1995)

Note: Both surveys investigated numerous sites across the Solway, but Powfoot and Kennethbank are the only two which are common to both.

Table 3.3 Sediment size analyses of selected marshes in the Solway Firth (data from Marshall, 1962 and Rendall and Bell, 1995)

The source of the sediment is principally glaciogenic sediments from bed of the Irish Sea (Rowe, 1978). Marshall (1962) concluded that the similarity in the percentage of fine silt across the Solway marshes and tidal flats implies that the source of the material is the same, coming from a marine rather than fluvial origin. The low discharges and gentle gradients over which the main Solway rivers flow (Marshall, 1962), suggest that only a small quantity of suspended sediment is supplied to the Solway from terrestrial sources (Steers, 1973). The competence of the rivers will only accommodate the transport of clay sized sediment, and this may account for the higher percentage of clay particles than silt measured by Marshall (1962).

The sediment is brought into the Solway by tidal action rather than wave activity, although wave action may erode existing sedimentary deposits, providing a local source of reworked sediment (Marshall, 1962). Experimental sea-bed drifters released into the Solway, penetrated the inner Solway only at the time of the equinoxes illustrating the importance of high energy tidal conditions to transport material into the Firth (Perkins *et al.,* 1962-63). This was also suggested by Babtie *et al.* (1966) who noted that during tidal bores, the seawater was highly turbid because of the heavy burden of sediment in suspension. This dependence upon large tides to transport sediment into the Firth means that deposition is an intermittent process (Perkins, 1966).

Perkins (1966) considers there to be a lack of silt within Solway deposits, resulting from the enclosed nature of the Firth, which facilitates deposition of silt on the seabed, rather than intertidal regions. In comparison, east coast estuaries, as a consequence of the open nature and long fetches of the North Sea, have a much larger component of silt within their sediment budgets. Only large tides have the current velocities to erode silt from the sea bed and transport it into the intertidal areas.

The exact source of silt entering the Solway was considered by Perkins (1966) to come from a source west of the Isle of Man, carried by a residual current. It was also concluded that there was no evidence for significant transport of silt by residual currents from St. Bees Head and the sea-bottom to the south. However, sediment contaminated with Sellafield-derived radionuclides, is known to be deposited within the Solway. If

Perkins' conclusions are correct, sediment transported from the easternmost part of the Irish Sea must do so in suspension rather than along the sea bed. This may be a further reason for the large quantity of clay sized particles in deposited sediment found by Marshall (1962).

While much of the sediment carried up-firth by flood tides is carried out again by the ebb, the long-term trend is one of gradual accretion in the areas of slacker water within the upper estuary (Babtie *et al,* 1966). The tidal asymmetry in the inner firth means that sediment carried by the flood tide is not completely carried out by the ebb. Perkins and Williams (1965) noted that a difference in velocity between the flood and ebb tide of between 0.26 m s^{-1} and 0.39 m s^{-1} is sufficient to ensure a preferential movement of sediment towards the inner part of the estuary. Given that the difference in Solway spring tides is 0.7 m s^{-1}, the process of infilling is strong. An easterly long-shore drift also encourages the movement of sediment towards the head of the firth (Marshall, 1962).

The highly mobile nature of the main tidal channels, resulting, partly, from the lack of silt adding cohesion to the sediment (Perkins, 1968), has made navigation in the Solway extremely difficult. Attempts were made by the Nith Navigation Company, in the 1860s, to constrain the River Nith within rubble walls but by the 1920s these had all but collapsed (Bridson, 1979). The volatile nature of the channel positions are well known to local fishermen and are extremely dangerous.

3.1.4 Development of the Solway saltmarshes

Sediment brought into the Solway is deposited in intertidal areas sheltered from significant wave action. The sand flats of the Solway form one of the largest continuous intertidal areas in Britain, covering some 42056 ha (Buck, 1993), comprising 7% saltmarsh, 59% intertidal flats and 34% subtidal areas (Black, *et al.* 1994). Both the bays in the west and the low sheltered coast in the east provide ideal conditions for marsh development. The marshes along the Solway coast can be found in a number of physiographic settings but can collectively be described as estuarine (Marshall, 1962).

The location of the marshes and their areas are shown in Figure 3.3.

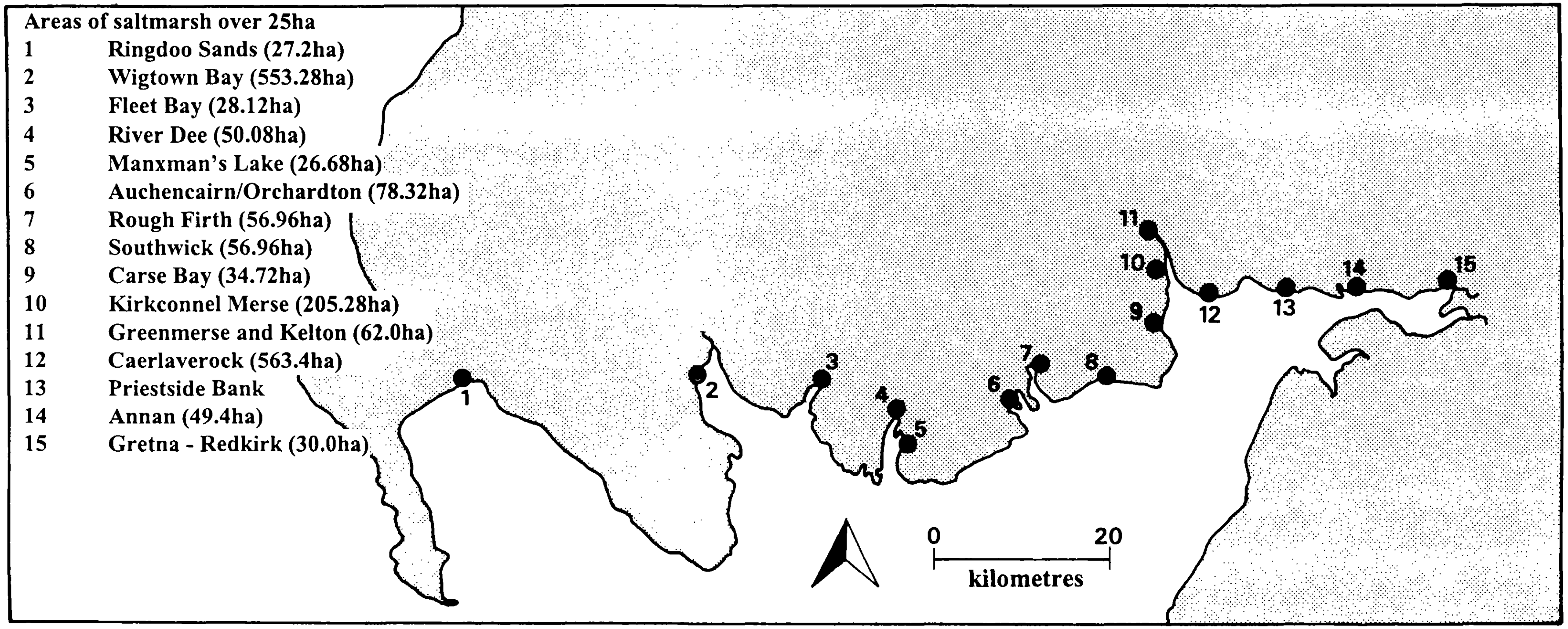

Figure 3.3 Major areas of saltmarsh along the northern Solway coast (from Burd, 1989)

Rowe (1978) calculated that between 1946 and 1973 there was a net gain by accretion of 383 ha in the inner Firth (including the English marshes). Pye and French (1993) suggest that the inner Solway marshes are currently experiencing dominant net erosion, despite the continual infilling of sediment, although they also note there are significant areas of lateral accretion. They arrive at this conclusion because of extensive erosion of some the largest marshes, such as the western side of Caerlaverock and parts of Burgh Marsh, on the English side of the Solway. Nevertheless, many of the smaller marshes are accreting, particularly those in sheltered bays, as shown by comparison of 1: 25 000 scale maps (Figures 3.4 - 3.6). Some of the marshes appear to be accreting vertically, as well as horizontally, demonstrated by the respective locations of the MHWS (Figure 3.7). Vertical accretion, however, can only be accurately determined by actual measurement of accretion rates. In the Inner Solway, Marshall (1962) measured high mean accretion rates at low marsh levels, 3.2 cm yr^{-1} at 4.6 m O. D, but which reduced rapidly to 1.3 cm yr^{-1} at 4.9 m O. D.. Above that level, the marker coal dust used was barely covered. Radionuclide analysis of two sediment cores from Southwick Merse indicated accretion rates of 6.5 cm yr^{-1} and 3.2 cm yr^{-1} (MacKenzie *et al.,* 1994). While these two cores were taken close to each other near the edge of the marsh, the difference in rates was not explained.

Erosion of the marshes in the Solway is attributed to two processes: wave action and fluvial action (Marshall, 1962; Rowe, 1978). Swell waves are limited and erosion, caused by wave action, is determined by the strength and direction of the wind (Black *et al.,* 1994), the greatest erosion occurring when the wave approach is normal to the coast. This is happening at the western end of Caerlaverock marsh. Fluvial erosion is caused by a river channel undercutting the marsh, leading to the marsh edge slumping. Again this is dramatically illustrated at Caerlaverock where both the Nith in the west, and Lochar Water in the east, erode the edge of the marsh as their courses migrate. In these situations however, it is unlikely that the actual erosion is caused by river water because of the low flows, and therefore low energies, which these rivers have. The erosion is more likely to be caused by flood tidal waters as they progress upstream in the channels, although this has not been investigated in depth.

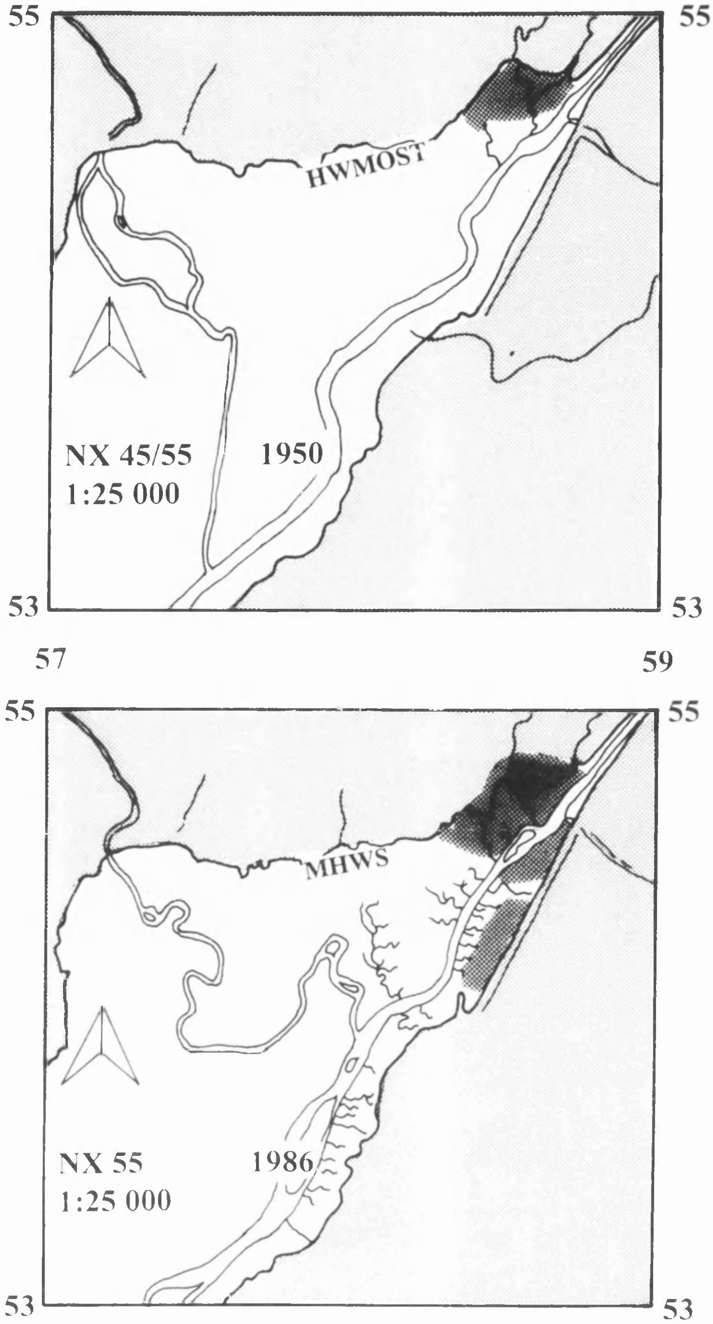

Figure 3.4 Development of saltmarsh in Fleet Bay

Legend for Figures 3.4, 3.5, 3.6 and 3.7

(shaded box)	Saltmarsh
(box)	Land
(box)	Intertidal area
(line)	HWMOST/MHWS
(line)	Stream/tidal channel
HWMOST	High Water Mark of the Ordinary Spring Tide
MHWS	Mean High Water Spring

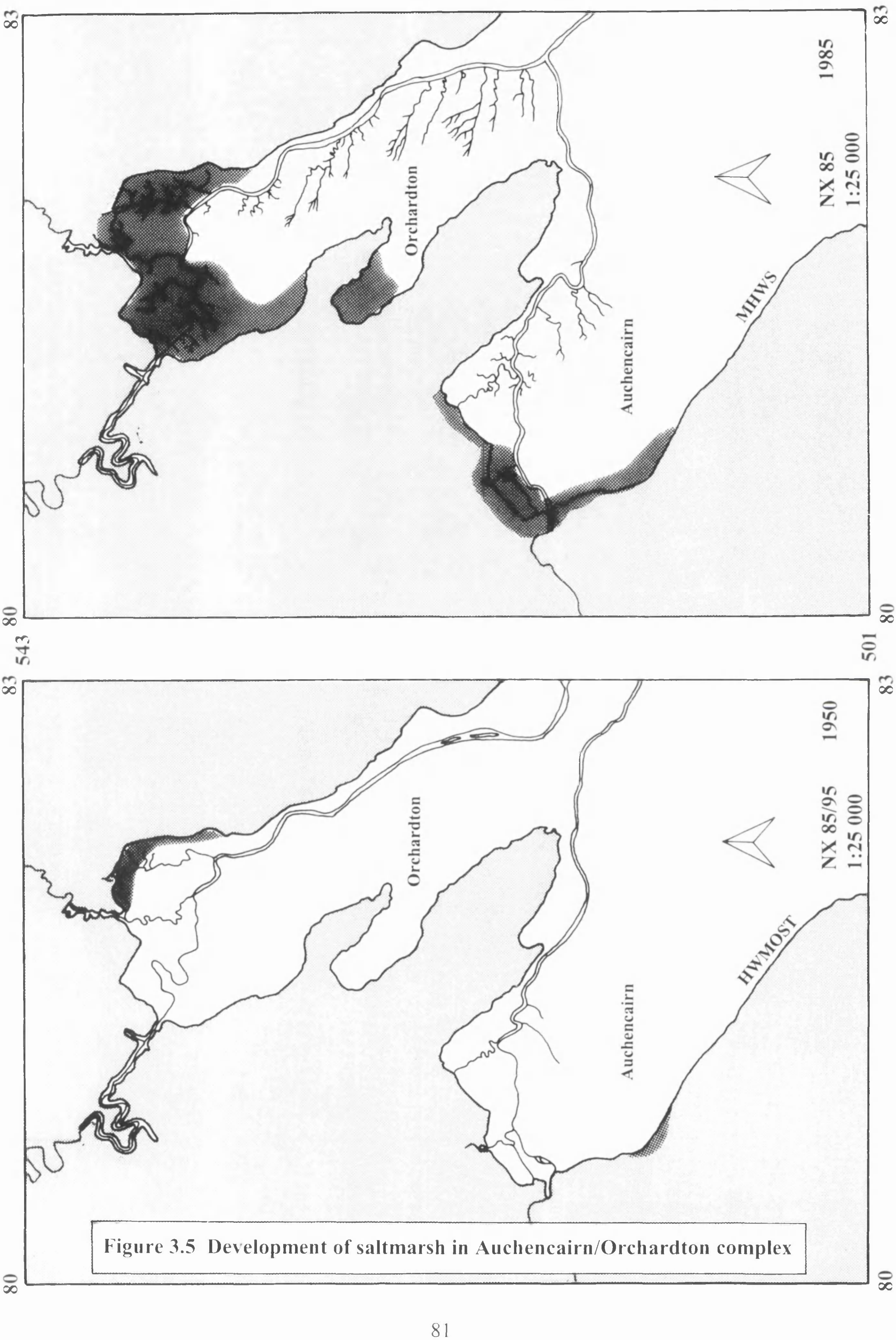

Figure 3.5 Development of saltmarsh in Auchencairn/Orchardton complex

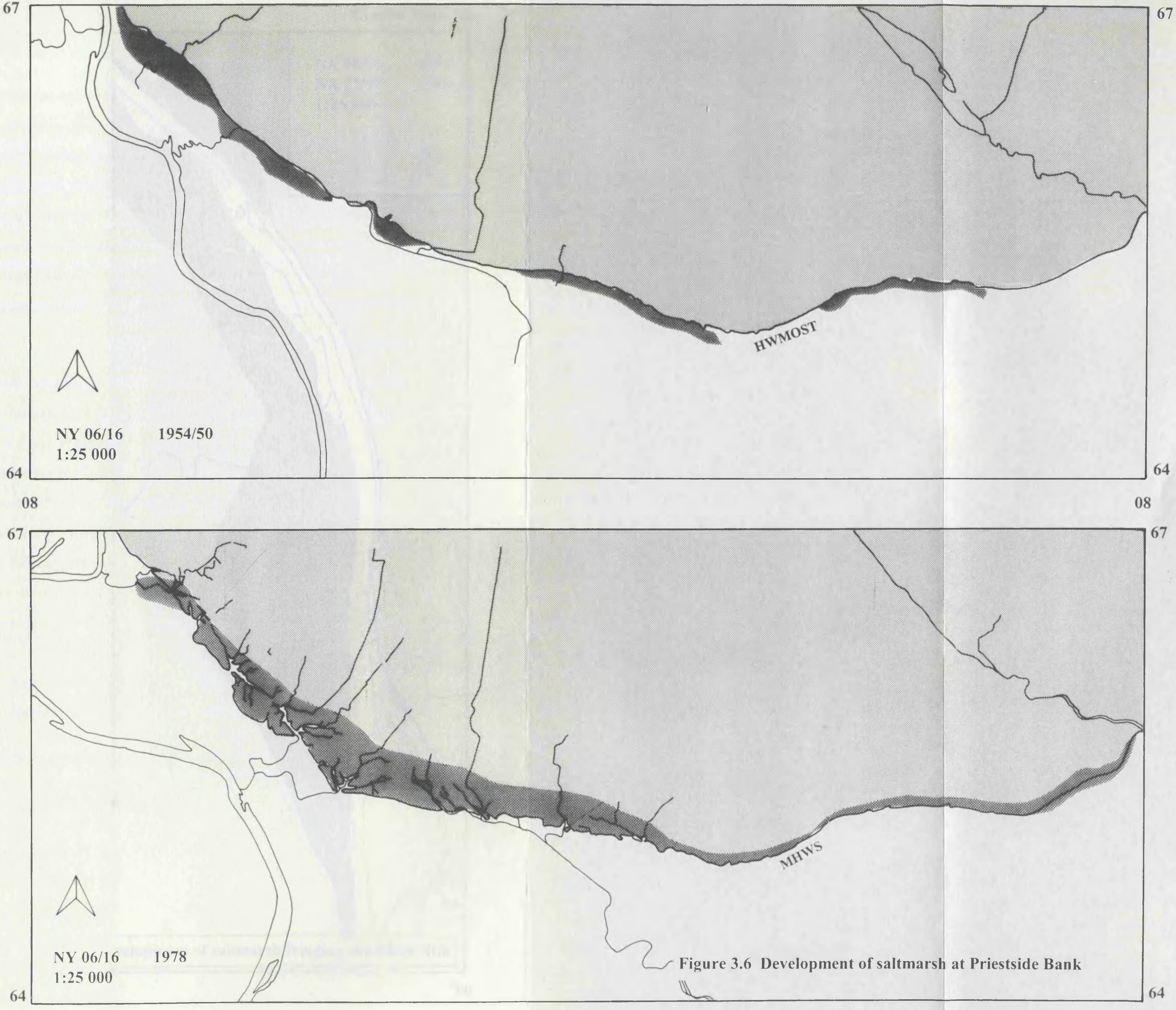

Figure 3.6 Development of saltmarsh at Priestside Bank

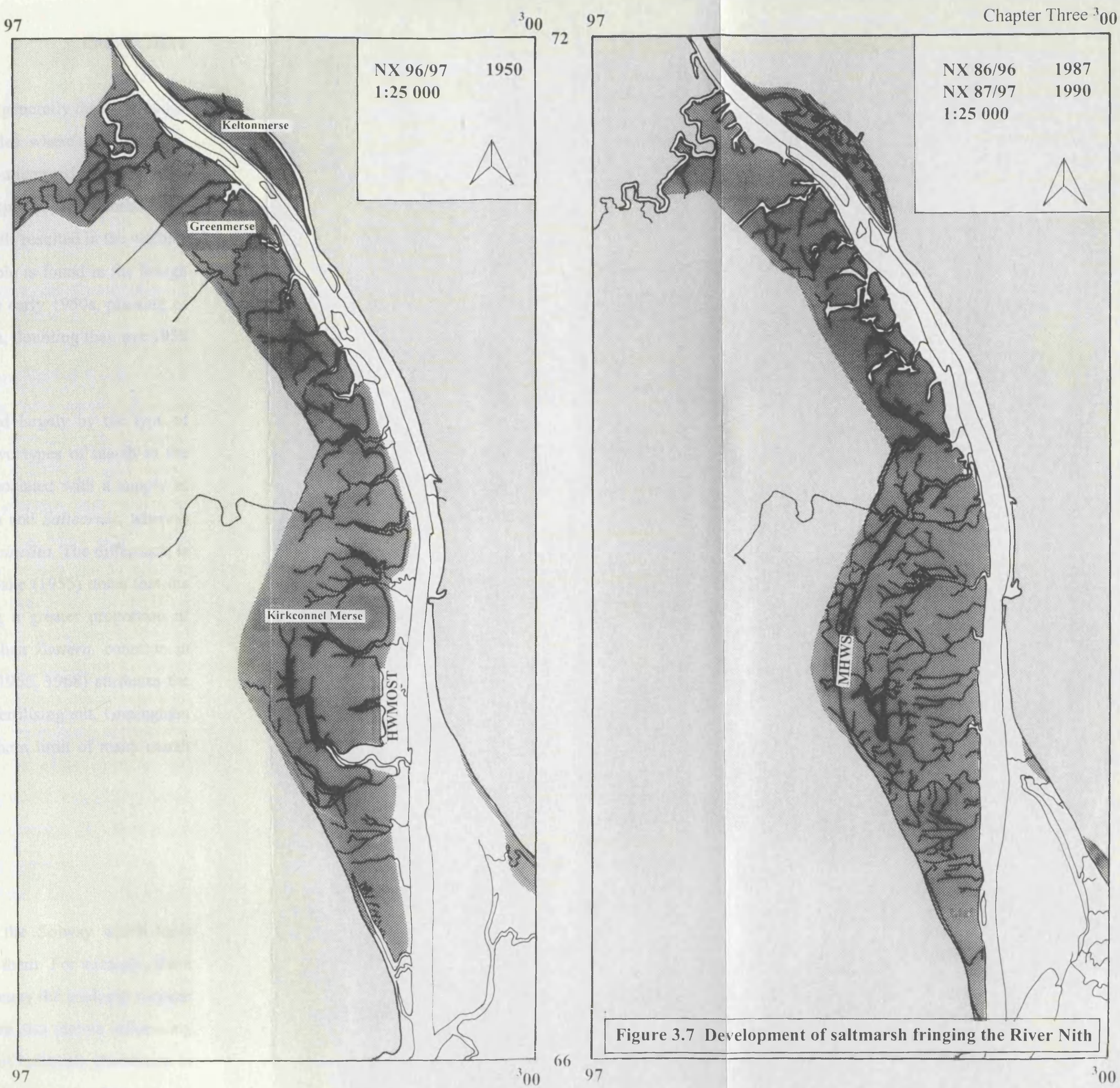

Figure 3.7 Development of saltmarsh fringing the River Nith

While processes of accretion and erosion in these marshes are generally the same as for other allochthonous marshes, there are a number of examples where anthropogenic intervention has directly influenced marsh development. The attempted channelisation of the River Nith, mentioned above, resulted in the rapid expansion of Caerlaverock marsh until the 1920s, but subsequent erosion of the rubble walls resulted in the western bank of the Caerlaverock marsh being eroded. Another example is found in the Rough Firth and the Auchencairn/Orchardton complex where, in the early 1950s, planting of *Spartina anglica* resulted in rapid expansion of the marsh area, doubling their pre 1950 size (Burd, 1989).

The vegetation species colonising the marshes is determined largely by the type of sediment deposited. Perkins (1968) differentiates between two types of marsh in the Solway. The marshes from Wigtown Bay to Southwick, associated with a supply of subtidal silt, have relatively well developed zones of *Zostera* and *Salicornia,* whereas the marshes of the inner Solway are colonised initially by *Puccinellia.* The difference, is attributable to the amount of silt supplied to the marshes. Blake (1955) notes that the sandy nature of the saltmarshes is demonstrated by having a greater proportion of *Puccinellia,* a feature common in many Scottish marshes, than *Zostera,* common in more muddy east coast marshes in England. While Perkins (1966, 1968) attributes the lack of species richness in the Solway marshes to a lack of fertilising silt, Gimingham (1964) suggests it is because the Solway represents the northern limit of many marsh species, especially *Halimione* and *Limonium* spp..

3.2 Classification of Solway saltmarshes

3.2.1 Problems associated with saltmarsh classification

Clearly, there are a number of different marsh types in the Solway which have developed as a result of different physical factors acting on them. For example, there appears to be a distinct difference between marshes which occupy the enclosed western and those on the low- lying eastern part of the Firth. There are also factors influencing all the marshes to a similar degree, such as a common source of sediment. Discussion in Chapter two indicated a number of parameters which define the location, character and dynamic nature of saltmarshes. In order to identify which of these parameters influence the variability in sedimentation, and therefore, radionuclide concentrations and distributions in the Solway marshes, it is necessary to establish those elements and factors common to the Solway marshes. Classification of the Solway marshes will assist this process.

Prior to considering the classification of the Solway saltmarshes, the classification of marshes as a whole, including those within the UK, needs to be considered.

The coastal environment has traditionally been classified using physical characteristics such as tectonics, physiography, sediment supply, sea level, tidal range and wave energy. Wetlands* are also typically classified using physical characteristics including geomorphic, hydrologic and edaphic parameters (Cowardin *et al.,* 1979; Brinson, 1993). Saltmarshes, however, have been classified using both physical and biological characteristics depending on the expertise or requirements of the investigator. Adam (1990) suggests that the latter is of more utility because vegetation can be used to recognise common marsh types as well as providing an indication of the physical characteristics which exist within that marsh. Adam argues that while vegetation can provide an indication of physical characteristics, similar physical environments can be colonised by very different biota. This means that a classification based solely on physical features may not predict the marsh vegetation likely to colonise a particular site. The opposite of this may also be true. Some marsh species have large distributional limits and are present in a wide range of different environments, suggesting that a vegetational classification may not fully predict physical characteristics. This ambiguous situation is illustrated by the classification of North American marshes on the basis of plant associations, producing three major groups: Bay of Fundy and New England;

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* The term wetlands is a relatively recent collective term to describe terrestrial environments which experience extensive (but not necessarily frequent) flooding allowing the subsequent development of hydrophytic vegetation. Such environments include saltmarshes, swamps, fresh marshes, bogs and similar areas.

Atlantic and Gulf coasts, and; Pacific marshes (Chapman, 1974). Frey and Basan (1978), however, point out that "west coast marshes are by no means homogeneous from Arctic Alaska to arid Mexico" and suggest that further division of these marshes could be achieved by including geological (tectonic and sedimentological) criteria.

Classification (of any object) requires, firstly, that the main features of the object are characterised and ordered and secondly, that the criteria upon which the classification is to be based, and the objectives of the classification, are defined (Perillo, 1995). Therefore, the main features which characterise saltmarshes must be identified and the classification criteria, either physical or ecological, must be determined. The main features of saltmarshes are tides, sediment, vegetation and such like, but the relative importance of these in the development of marshes is, as shown in Chapter two, disputed. Frey and Basan (1978) identify a number of defining parameters (Box 3.1), with vegetation being the most important.

1. the character of and variability of the marsh vegetation;
2. the effect of climate, hydrology and soil conditions on the flora;
3. the nature (source, composition, compaction, deposition) of the marsh sediment;
4. organism-substrate relationships, both by fauna and flora (for example burrowing and the influence of plants on marsh accretion);
5. extent of depositional surface and relative topography;
6. tidal range;
7. wave and current energy;
8. structural stability of the coast.

Box 3.1 Variables affecting difference in marsh types (after Frey and Basan, 1978)

Adam (1978) attributes much saltmarsh variation in Britain to site management (livestock or avifaunal grazing) and historical development of the marsh, including the construction of seawalls and embankments. The importance of hydrology in wetlands as a whole, is stressed by Kangas (1990) and Holland (1996). Allen and Pye (1992) suggest that saltmarsh location and behaviour is governed by only four physical factors: sediment supply; tidal regime; wind-wave climate and; the movement of relative sea level, with vegetation playing a variable but secondary role.

Differences between the two methods of classification, physical and ecological, also emerge in defining the classification objectives and the criteria which are to be used to execute the classification. Physical classifications consider marshes as complete individual units. Marshes are grouped on the basis of broad physical characteristics, primarily physiographic location, although tectonic stability of the coast, sediment supply and type and tidal characteristics are also used. This creates a broad generic classification in which marshes are not associated with any particular geographical location. Ecological classifications divide individual marshes into communities and use the distribution and successional associations of these, based largely on climatic and tidal considerations, firstly, to determine the limits of vegetation species and secondly, to group geographically distinct marsh types. The success, or otherwise, of these two methods will be explored in the following sections.

3.2.2 Ecological classifications

Perhaps the most widely used ecological classification of the world's saltmarshes is that of Chapman (1974, 1977), who suggests that "the world-wide spread of dominant genera exerts some influence upon the type of classification that can be employed for wet coastal formations". Chapman identifies broad geographical groups which, although based on species abundance, indicate broad variations in the climate, tidal conditions and tectonics which influence saltmarsh development. These groups are listed in Box 3.2.

Major Groups	Subgroups
Arctic	
North European	Scandinavian, North Sea, Baltic, English Channel, south-west Ireland
Mediterranean	Western Mediterranean, Eastern Mediterranean, Caspian
Western Atlantic	Bay of Fundy, New England, Coastal Plain
Pacific American	
Sino-Japanese	
Australasian	Australian, New Zealand
South American	
Tropical	

Box 3.2 Classification of world saltmarshes (based on Chapman (1974, 1977))

The north European group, of which the Solway can be considered part, is further sub-divided into groups based upon soil type and distinct geographic locations (Box 3.3). Chapman (1974) accepts that there may be some differences in the physiography of the marshes, but asserts that they conform to a definite geomorphological pattern. The meaning of this, however, is unclear. Different saltmarshes do have common geomorphological features such as creeks and pans, but the distribution of these is determined by a number of different factors, such as the tidal velocity, substrate type and sedimentation rates. These factors will, in turn, influence the distribution and abundance of certain vegetation species.

North European subgroups	Description and location
Scandinavian	Sandy and sandy-mud substrate developed on a rising coast. Dominated by grasses, esp. *Puccinellia maritima, Festuca rubra* and *Agrostis stolonifera.* Found in Scandinavia, Schleswig-Holstein, west coast of Britain from the Severn to northern Scotland, east coast of Eire, east coast of Scotland from Kincardine to Inverness.
English Channel	Soil soft clay or silt mud. Dominance of *Spartina townsendii* and *S. anglica.* Found on both sides of English Channel
North Sea	Firm mud type with more silt and clay, associated with subsiding coastline. Wide range of vegetation communities with less grass than the Scandinavian group and more herbs, e.g. *Aster tripolium, Limonium* spp., *Ameria maritima* and *Plantago maritima.* Introduction of *Spartina townsendii* and *S. anglica.* Located in eastern England, south-eastern Scotland, northern Germany, coasts of Holland and Belgium.
Southwest Ireland	Peaty soil due to limited sediment supply
Baltic	Brackish conditions but similar to Scandinavian and North Sea subgroups but presence of *Carex paleacea, Juncus bufonius and Desmoschoenus bottnica.* Primary colonist *Scirpus.*

Box 3.3 North European subgroups (based on Chapman (1974, 1977))

Chapman (1974) stresses that in studying saltmarsh vegetation, the seral (successional) character of saltmarsh vegetation implies that "allogenic and autogenic components" should be determined. Allogenic components are physical characteristics such as tidal inundation, movements of the water table and sedimentation rates which preferentially influence the lower parts of the marsh. Autogenic factors, important in the high marsh environment, are imposed by the plants themselves, for example, increase in soil organic matter, competition and available light. Paradoxically, these factors are not, however, a component of the classification presented by Chapman.

The lack of cohesion between physical and ecological aspects of saltmarsh classification is reiterated by Beeftink (1977) who identifies and describes the distribution of nine saltmarsh communities within western and northern Europe. The association of different communities within individual marshes determines the category into which a marsh is placed. In addition to this, Beeftink distinguishes six types of saltmarsh based on conditions of salinity and tidal range: estuarine, Wadden (barrier island), lagoonal, beach plain, bog and polder type. The two different methods of saltmarsh division are not, however, integrated which, inappropriately, suggests that marsh vegetation is divorced from the environmental conditions which exist on the marsh.

A classification for British saltmarshes is presented by Adam (1978) as an updated and more communicable ecological classification. Chapman's classification is criticised by Adam (1978), not in terms of the conclusions, but because of the methodology used. It is argued that Chapman's classification framework, originally devised in 1941, is too simplistic being based on only a few saltmarshes and subsequent site investigations have identified anomalies in the broad categories. Problems also arise with Chapman's use of a seral classification strategy: that is, the identification of successional trends and the use of dominant species within the community. Adam (1981) suggests that areas represented by pure stands of species are easily ascribed a community name but this process is difficult in the case of more species-rich communities. This reduces the value of that community name being used as an aid to communication between researchers in different areas.

Many of the problems in this scheme stem, not from Chapman's original classification of communities, but from the interpretations and adaptations made by subsequent authors. Chapman's communities were determined using vegetation from Scolt Head Island in north Norfolk which may not provide the range of communities needed to allow classification of all British saltmarshes. Chapman's original community descriptions have been adapted for use in different regions, therefore making direct comparison between studies unreliable.

The classification system devised by Adam (1978, 1981) is based on standard phytosociological techniques, identifying vegetation communities based on their total floristic composition and the degree of internal heterogeneity, rather than using species dominance. Adam identifies some 64 saltmarsh communities within the British Isles, with the communities grouped into 10 group noda (each group nodum contains between 3 and 9 communities or noda). The distribution of the group noda allows a three fold division of the British saltmarshes to be recognised. For example a high representation of nodum groups I and II (shown in Box 3.4) is concentrated in south-east England. These are designated as Type A saltmarshes. Type B saltmarshes are located mostly along the west coast of England (the Solway marshes are included in this group) and differ from Type A in a general decrease in the representation of group II noda and an increase in groups IV and V. Type C marshes are all in western Scotland where only a few noda occur.

There is some similarity between these groupings and those by Chapman, although the divisions made by Chapman are more instinctive and are therefore more understandable.

Nodum I	**Nodum II**
1. Spartinetum townsendii	1. *Aster-tripolium* var. *discoideus* nodum
2. Salicornietum europeanae	2. *Limonium-Ameria* nodum
3. *Puccinellia-Salicornia-Sueda* nodum	3. *Triglochin-Juncus maritimus* nodum
4. Species poor *Puccinellia* nodum	4. Halimionetum portulacoidis
5. Moderately species-rich *Puccinellia* nodum	5. Puccinellio-Halimionetum portulacoidis
	6. Artemisietum maritimae
	7. Atriplici-Agropyretum pungentis
	8. *Agropyron-Juncus maritimus* nodum

Box 3.4 Communities or noda of Nodum Groups I and II (from Adam 1978)

3.2.3 Physical classifications

Numerous authors have identified groups of physically distinct marsh types based on their physiographic location as summarised in Box 2.1 (Chapter two). The inclusion, as a separate unit, of marshes which have been altered by human intervention is questionable. The most common type of adaptation is reclamation of the saltmarsh, usually by the construction of a sea wall or embankment, to provide grazing land for livestock and on some marshes this practice has been carried out for many years. For example parts of the Severn Estuary (Allen, 1992a) have been reclaimed since Roman times. Although such marshes maintain a residual saltmarsh flora (Long and Mason, 1983), this may be due to the tenacity of the plant species rather than a deliberate attempt to maintain the nature and character of a saltmarsh on the reclaimed land. Many marsh plants with terrestrial origins (Adam, 1990) have adapted to saline conditions but are not necessarily halophytic genera (Carter, 1988) and actually perform better in non-saline environments (Chapman, 1974). Reclaimed marshes may therefore retain marsh vegetation but cannot be considered active marsh because they do not adhere to the definition of a saltmarsh as outlined at the beginning of Chapter two, in that they are not frequently inundated with saline tidal waters.

In addition to these very broad physiographic classifications, two other classifications have been constructed using physical characteristics. The scheme by Dijkema (1987) is based on geological development and morphology and is specifically designed to be used with maps and aerial photographs. This classification, given in Box 3.5., draws on two main sources for its inception: a coastal classification by Shepard (1963) and saltmarsh types identified by Beeftink (1977). The former stresses the importance of modification of the coast by marine processes and to this end, the coast is divided into primary and secondary coasts. Primary coasts exist where the sea lies against a landform shaped by terrestrial geological processes. Secondary coasts are formed by present day marine processes with their morphology being determined principally by tidal range. These broad divisions are translated into rocky shores and marine sedimentary shores by Dijkema (1987). Also included for the purposes of saltmarsh classification are fluvial sedimentary shores which, although terrestrial, (and would therefore be considered a primary coast by Shepard) display contemporary sedimentation. These are also important in that the fresh water input to a saltmarsh system will influence the type of colonising vegetation.

Substrate	Geology	Saltmarsh Type
Allochthonous	rocky shores	ria bay loch/fjord head beach head
	marine sedimentary shores	barrier-connected lagoonal foreland estuarine
	fluvial sedimentary shores	deltaic
Autochthonous	shore types	emerging flat shore emerging skerries peat
	inland types	white alkali soil black alkali soils

Box 3.5 Classification of European saltmarshes and salt steppes (Dijkema, 1987)

The saltmarsh types identified by Beeftink (1977) were assigned to these three main divisions, with the exception of the bog type. Dijkema argues that coasts emerging due to isostatic readjustment, excluded by Shepard's classification, are also important locations for saltmarshes, especially around the Baltic. These, together with inland saltmarshes, salt steppes and the bog type identified by Beeftink, create a group of saltmarshes maintained by autochthonous sedimentation, principally the in situ decay of organic matter. According to Dijkema (1987) these occupy only 3% of European saltmarsh areas, although they are certainly more prevalent in other parts of the world such as the south-eastern coast of the USA. The saltmarshes on rocky shores and on sedimentary shores are maintained largely by inorganic sedimentation coming from marine or fluvial sources and are, therefore, grouped as allochthonous saltmarshes.

The classification by Stevenson *et al.* (1986) divides marshes into six types (Box 3.6) based on "marsh response to extrinsic forcing functions", that is, the response of marshes to changes in sea level. There are some similarities between this and other physically based classification systems; for example, the emerging coast type is similar to Dijkema's rocky shore category. While Stevenson *et al.* (1986) admit that "most of the categories are highly aggregated", the categories which have been identified are unworkable on a global scale, as is intended by the authors. Many of the examples are located in North America and it is likely that the classification will only be applicable there.

Marsh Type	Characteristics
Emerging Coast	Common along tectonically active coasts, e.g. Alaska, Scandinavia; marsh development restricted where emergence is significant; relatively rapid succession from halophytic to glycophytic species.
Submerging Coast	Submerging coast with high salinities, including Florida, northern Europe, majority of coasts of Asia, Africa and South America; distinct differentiation between low and high marsh because of low total suspended sediment; where TSS is high, the low marsh is replaced by well developed levees; net export of sediment measured in middle Atlantic and south-eastern coastal plain of US.
Estuarine	Located in areas with abundant sediment; marshes characterised by streamside levees with lower elevation backmarshes; high rates of sedimentation due to allochthonous inputs.
Submerged Upland	Brackish marshes that develop on recently submerged coastal terraces under low tidal ranges; limited supply of sediment; marsh sediment draped as a veneer over recently submerged upland soil profile.
Floating Mat	Constitute a large proportion of coastal wetlands on Gulf of Mexico and sporadically in rest of world; related to degraded marshes where the peat mat has broken loose from the subsiding substrate; floats with the rising tide and therefore has little access to inorganic sediment supply.
Tidal Freshwater	Located at the head of estuaries where tidal waters are strong but with very low salinities; accrete rapidly because of riverine inputs.

Box 3.6 Sedimentary tidal marsh types (after Stevenson *et al.*, 1986)

The defining characteristics of the categories presented by Stevenson *et al.* (1986) are very generalised and, perhaps, misleading. Submerging coastal marshes are characterised by a net export of sediment but they are able to accrete sufficient material to keep pace with sea level rise due to the influx of sediment during storm events and autochthonous sedimentation from vegetation. Not all submerging coasts are subject to a net export of sediment: many saltmarshes around the world are subject to relative sea level rise but still accrete sediment via tidal inundation. This is not mentioned in the characterisation of the classification. The estuarine marsh is characterised with having streamside levees and lower elevation backmarshes but these features are also found in physiographic locations other than estuaries. The classification also suggests that only estuarine marshes accrete via tidal inundation which is inappropriate. Many saltmarsh types around the world experience sea level rise conditions and are capable of accreting sufficiently via tidal inundation, producing the 'typical' saltmarsh profile of a low and high marsh with levees at the creek banks. It is also debatable whether the tidal freshwater category really belongs in a saltmarsh classification system, since they lack the fundamental feature of saltmarshes, that is, saline inundation.

3.2.4 Assessment of saltmarsh classifications

It must be reiterated that before a classification can be devised, the criteria upon which the classification is to be based, and the objectives of the classification, must be defined. For ecologists, the objective is to classify saltmarsh vegetation into recognisable communities and associations, rather than to assign an individual marsh to a group type, as attempted by physical classifications.

That there is a widespread occurrence of dominant genera in saltmarshes around the world is both an advantage and disadvantage when trying to construct a viable ecological classification of saltmarshes. The definition of broad global groups based on the identification of dominant species, as adopted by Chapman (1974, 1977) and updated by Adam (1990), is useful because, although the groups are based on species abundance, they indicate broad variations in the climate, tidal conditions and tectonics which influence saltmarsh development. Adam (1990) recognises that the macroscale*, patterns in saltmarsh vegetation reflect the effects of climate and past events which have modified the species seed bank.

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* Variation occurs from regional (hundreds of kilometres) to continental scale.

Difficulties arise when trying to classify saltmarshes within a meso-[†] or micro-scale[‡]. Many identified saltmarsh communities are dominated by several species, creating difficulties in assigning a community name to an assemblage of plants. Another problem manifests itself because, within individual saltmarshes, different communities occupy different parts of the marsh. For example, the *Puccinellia maritima* dominated community favours low marsh environments, whereas, the community dominated by *Halimione portulacoides* is frequently found on the banks of creeks. Moreover, individual communities can occupy a number of different environments. For example, the *Puccinellia-Salicornia-Suaeda* community occupies four completely different environments (Adam, 1981) as shown in Box 3.7.

1. on the sides of large creeks;
2. on sandy marshes where the micro-topography is subdued, the nodum is a pioneer;
3. on sandy marshes with a hummocky topography, the nodum is found at the top of the hummocks
4. on muddy marshes the nodum is found in depressions

Box 3.7 Environments of the nodum *Puccinellia-Salicornia-Suaeda* (from Adam, 1981)

Confusion in the current ecological classifications arises because authors (e.g. Chapman, 1974, 1977; Beeftink, 1977 and Adam, 1981, 1990) ascribe the *distribution* of saltmarshes to physical rather than ecological parameters, yet approach *classification* from an ecological perspective. Perhaps the most limiting aspects of ecological classifications is the amount of field evidence required in both their creation and use, and of the inaccessibility of the classification to non-ecologists because the "awkward European system of nomenclature is not appropriate" (Stevenson *et al.*, 1986).

[†] Variation operates over scale of tens to hundreds of kilometres.

[‡] Scale operates over metres to tens of metres.

An alternative is achieved by Dijkema (1987) who uses sediment type, marine conditions and physiographic location as a basis for classification, which has the immediate advantage of being accessible through the use of aerial photographs and maps. This physical classification can be used at a number of geographical scales, although it is perhaps of most use at the meso-scale where the influence of tidal conditions and geology is most acute.

Within each of the saltmarsh groups identified at the meso scale, variation will exist in the vegetation distribution and community relations. Vegetation will have a large influence on the physical parameters working at the micro-scale, such as the sedimentation rates and hydrology, but the physical characteristics will also influence which species colonise. This inter-relationship between vegetation and physical characteristics is perhaps easier to handle at a small scale and vegetation can be used as a third tier of classification.

3.3 An integrated saltmarsh classification

The inadequacies of current classifications can be illustrated in the Solway. The Solway Firth saltmarshes lie within Chapman's west coast sere or can equally be described as estuarine under Dijkema's system. Both these classifications hide the fact that there is considerable variation in the 26 Solway marshes with respect to their physiographic location, sediment characteristics and vegetation, illustrated in section 3.1 above. In order to be useful, a classification is required which can accommodate differences in individual marshes, located within a relatively small geographic area.

Ideally, a saltmarsh classification should contain elements of both ecological and physical classifications and should be set within a scale hierarchy. Adam (1990) admits that "even if the (classification) units themselves are determined by botanical criteria, it is possible that the framework in which the units are disposed may be better based on other criteria (for example, geomorphological or hydrological)". It is only by doing this that a comprehensive and appropriate classification can emerge.

The classification proposed in this work, is shown in Figure 3.8. The initial tier of the classification is derived from Chapman (1974, 1977) which uses the distribution of the dominant marsh species to establish broad geographical units driven largely by climatic parameters. To augment this initial tier, a tripartite division of tides is used to clarify the relative importance of tidal range in each of the areas. The tide will not only shape the structure of coastal sedimentary features, but will also influence the type of sedimentation which occurs: authochthonous versus allochthonous.

The second tier of the classification is based on that of Dijkema (1987) and Beeftink (1977) which emphasises the interaction of wave and tidal conditions in saltmarsh development. Different physiographic locations influence the type and character of sedimentation. The dominance of physical processes in this classification stresses that the function of saltmarshes, and indeed all wetlands, is fundamentally based on geomorphology and hydrology (Brinson, 1993).

The next tiers of the classification relate to vegetation type and management at a marsh wide scale or on different parts of a single marsh. For example there will be very different floral communities occupying the low and high marsh areas. The morphological units, or sub-habitats suggested in the classification are derived from Ranwell (1972). This tier allows a comprehensive assessment of communities and their associations which can be related to the prevailing geomorphological or hydrological conditions on the marsh. Different marsh types arise not only through natural controls but also as a consequence of management practises such as grazing and the construction of sea walls and embankments. These aspects of saltmarsh development should be included within a classification system, especially if the management includes the introduction of new species for the purposes of sea defences, or if the grazing encourages a particular vegetation to become dominant.

This classification has a number of advantages. It can be employed at a number of scales using both physical and ecological characteristics. At a marsh wide scale it can be utilised using maps and photographs. The vegetational aspect of the classification can be carried out at a scale directed by the user, depending on the requirements of the project. This allows a large degree of flexibility and also means it is accessible to all disciplines. The main structure of the classification is based on the physical parameters which underpin the character of saltmarsh systems.

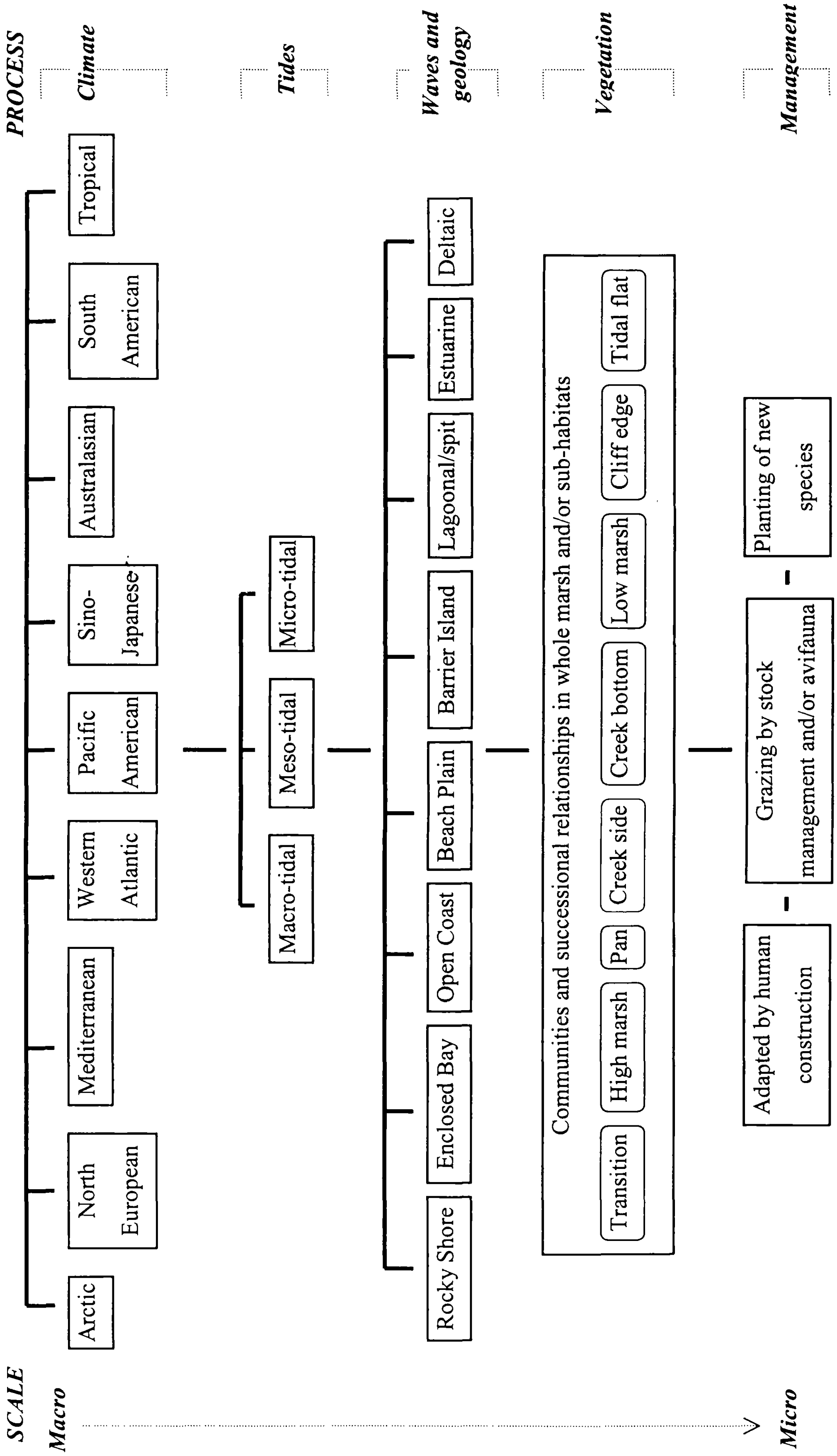

Figure 3.8 A hierarchical classification for saltmarshes

3.3.1 Re-classification of the Solway marshes

Using the general saltmarsh classification, the Solway marshes can be classified as shown in Figure 3.9. The Solway is part of the North European group and has a macro-tidal regime. The collective marshes could be classified as estuarine (Marshall, 1962) even though the riverine input for the Rivers Esk and Eden is small compared to the tidal volumes. Within this generalisation considerable variability exists if individual marshes are considered. The classification exercise was conducted using the available literature and 1:25 000 Ordnance Survey maps. Whilst these maps are extremely useful, they do not allow a detailed assessment of marshes less than 25 hectares in size. Saltmarshes below this size are too small to examine with any degree of accuracy on the 1:25 000 scale maps.* For ease, these were removed from the exercise, leaving 18 saltmarshes in the Solway to be classified.

Three geomorphic settings are represented in the Solway saltmarshes: there are 6 estuarine saltmarshes, 8 enclosed bay and 4 open coast types (the names of which are shown on Figure 3.9). The estuarine marshes are those which have a significant riverine input. While none of the Solway rivers has a high discharge, they will nevertheless influence the saltmarsh because of their freshwater input during flooding. The enclosed bay marshes are those within a bay formed by the structural geology rather than a river estuary. There may be a small riverine input, but this has little or no influence on the marshes as the fresh water does not cover the marsh surface, even during periods of high rainfall or snowmelt. There are no true open coast areas in the Solway because of the shelter afforded by the shape of the firth. Some, however, are relatively exposed to the main incoming tidal wave, and subject to a long wave fetch and are fronted by extensive tidal flats. This imparts open coast characteristics to such saltmarshes, especially at Caerlaverock saltmarsh and those on the outer part of Wigtown Bay.

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* The 1:25 000 map series are simply direct reductions of their 1:10 560 scale counterparts (Harley, 1975) and as such should not be used too literally.

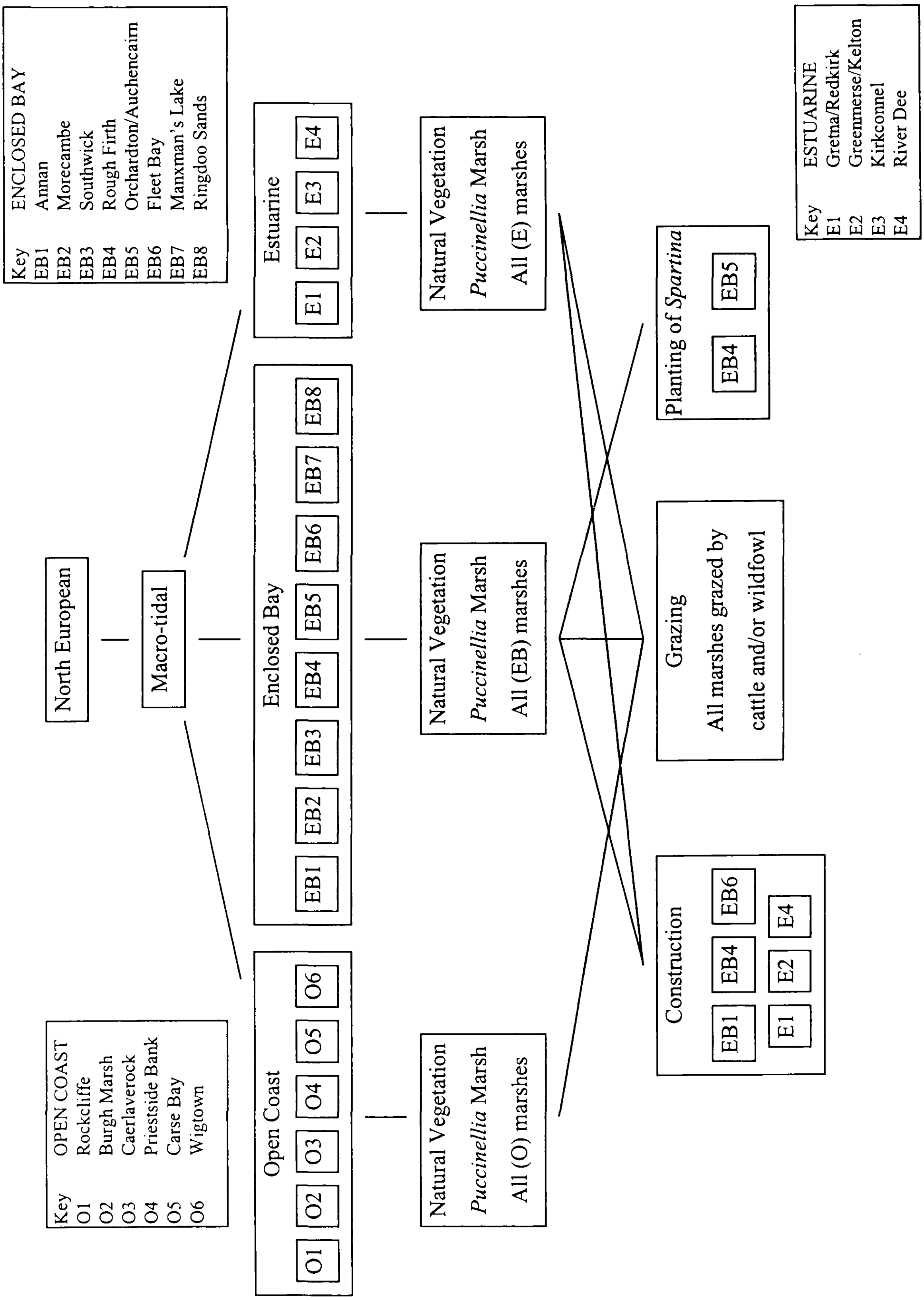


Figure 3.9 Classification of the Solway saltmarshes

The natural vegetation on all the Solway marshes begins with the pioneer species *Puccinellia maritima.* This gives rise to further colonisation by *Salicornia, Triglochin, Aster maritima, Limonium* and *Halimione* in the middle marsh areas. The high marsh is colonised by *Festuca* and associated species. On some saltmarshes however, the character of the vegetation has been altered by the introduction of *Spartina* in the early 1950s, designed to encouraged marsh extension. There are now a number of marshes which are almost completely dominated by Spartina, although remnants of the original vegetation exist at their landward ends.

A few of the marshes have been altered by the construction of sea walls and embankments, although the scale of development is very low. All of the marshes are subject to grazing by either cattle, sheep or wildfowl. Apart from this there is no active management of the marshes, except in Southwick where weed killer is sprayed to halt the spread of *Spartina* (Harvey and Allan, 1998).

This integrated classification of the Solway shows that there is a substantial amount of internal variation within the Solway Firth which should be considered when comparing and sampling individual marshes. The marshes will differ most significantly in their physiographic location and the planting of non-native species. It is these factors which will influence the resulting sedimentation patterns and radionuclide concentrations.

4. METHODS

4.1 Sampling strategy

The northern shore of the Solway Firth has 24 discrete saltmarshes which together account for 33.5% of Scotland's total saltmarsh area, amounting to some 2046 hectares (Burd, 1989). Careful and pragmatic sampling was required to ensure that the aims of the study were realised. The aims seek to investigate the influence of physiographic location on saltmarsh development and to determine how factors such as changes in vegetation influence the sedimentation rates and patterns in the Solway Firth. The classification outlined in Chapter three illustrates the saltmarsh variation which exists in the Solway thereby steering the sampling. In addition to this, logistical constraints such as access onto marsh areas and safety issues have to be appreciated and included in the sampling process.

As indicated in Chapter one, geomorphic investigations frequently employ a purposive sampling regime which relies on the judgement of the 'expert' investigator to choose an appropriate sample. There are problems with this strategy. Different 'experts' may well choose different samples and the objectivity or representativeness of the selection cannot be assessed (Harvey, 1969). This may lead to problems if inferences about the total population are to be drawn from the sample (Haynes *et al.*, 1982), especially those generated statistically. The Solway Firth saltmarshes are often discussed collectively which may be inappropriate given their variability: a variability not made explicit prior to the classification presented in Chapter three. Utilising inferential statistics to model processes in the Solway Firth as a whole, requires that samples be randomly selected, such that each has an independent and equal chance of being chosen. Random sampling requires that the investigator has no subjective input into the sample selection. These two strategies, purposive and random sampling, would appear incompatible but it is possible to utilise both within a single investigation.

The spatial distribution of geographic phenomena often appears to be chaotic and without structure, making the study of patterns and processes extremely difficult. The utilisation of an investigator's expert knowledge facilitates the study of spatial structures by enabling hypothesis formulation (Harvey, 1969). Indeed the imposition of structure is essential if logistical constraints are to be overcome. Subsequent random sampling allows conclusions to be assessed and, through statistical analysis, provides a means to test the hypotheses created. Indeed, the design of a random sampling programme will be aided by having an understanding of the structure of the phenomena which are being investigated. The procedure adopted here was to systematically sample from a stratified sample of saltmarshes. The stratification was based on the saltmarsh classification identified in Chapter three with one marsh sampled from each of the classification categories present in the Solway.

4.2 Site Selection

4.2.1 Marsh site selection

In order to establish which saltmarshes in the Scottish part of the Solway were to be used in this study the sites were classified according to the model presented in Chapter three (Figure 3.9). In order to use the readily available 1: 25 000 Ordnance Survey maps, only saltmarshes over 25 hectares in size were included. By classifying the marshes, the diverse Solway coastal environment is effectively stratified. Choosing a unit from each stratum ensures that the sample chosen is more representative of the whole than a simple random sample. (Wood, 1955).

There is a supposition by other commentators that all the Solway saltmarshes are similar and therefore have the same basic physical characteristics. The new classification shows that there are three geomorphic settings for the Solway marshes, each responding differently to energy inputs by the tide and waves present in the Solway Firth, resulting in divergent sedimentation patterns and perhaps vegetational changes. The three settings are open coast, enclosed bay and estuarine. These settings were further subdivided based on the management of the sites. This resulted in seven types of marsh, shown in Box 4.1.

Marsh Type	Locations
Open Coast, no adaptation	Caerlaverock, Priestside Bank, Carse Bay, Wigtown
Enclosed Bay, no adaptation	Southwick, Manxman's Lake, Ringdoo Sands
Enclosed Bay, *Spartina* planting only	Orchardton/Auchencairn
Enclosed Bay, construction only	Annan, Fleet Bay
Enclosed Bay, construction and *Spartina*	Rough Firth
Estuarine, no adaptation	Kirkconnel
Estuarine, construction	Gretna/Redkirk, Greenmerse/Kelton, River Dee

Box 4.1 Saltmarsh types in the Solway Firth

Ideally one marsh from each of the seven marsh types should be investigated to determine the effect of all geomorphic settings and the impact of all types of management. This project, however, endeavours to investigate saltmarshes in as natural a state as possible. Saltmarshes displaying potential or actual human modification resulting in the marsh being constrained in its movement or development were eliminated from the study. Such modifications include the construction of piers or sea breakers, sea walls and military use. Most of the saltmarshes along the Solway have not been reclaimed in recent times, unlike many of those in England, this being one of the reasons why the Solway was chosen as the study location. In addition, there has been little construction on this coast due to the lack of industry.

Many of the saltmarshes have embankments at their landward limit, constructed at the end of the 19th century, separating the saltmarsh from rough grazing land. At the time of construction, these bunds (embankments) will have undoubtedly influenced the development of the saltmarshes by preventing tidal waters penetrating to their limit on the land. During the last hundred years, most Solway marshes have extended seawards and in many cases the bunds now lie beyond the tidal limit and so exert no influence on marsh development. Locations where the bunds still constrain saltmarsh activity were not considered further.

While the planting of *Spartina* on some marshes has rendered them semi-natural, no further management of these sites has occurred. The character of these marshes has certainly been affected as a result of the planting and this change needs to be assessed, especially as it has a bearing on the sedimentation pattern of the marshes.

This project is concerned principally with the movement of marine and intertidal sediments onto the marshes which bring with them Sellafield derived radionuclides. Estuarine marshes will experience sedimentation from terrestrial as well as marine sources and are therefore outwith the area of concern in this study. Removal of this sub set leaves two types of saltmarsh which should be investigated.

This project aims to investigate both current and past sedimentation patterns of marshes in the Solway. In order to do this, the recent history of the marshes were determined using 1: 25 000 maps for the two time periods available, 1940/50s and 1970/80s. Marshes were described as either accreting or eroding. Some saltmarshes, especially those on the open coast, have experienced both accretion and erosion. As a result of this exercise the remaining marshes were further subdivided as shown in Box 4.2.

The outcome of the initial classification and assessment of the status of the marshes indicates that investigation of four marsh types will firstly, fulfil the aims of the project and secondly, provide a representative set of the Solway marshes.

Marsh Type	**Locations**
Open Coast Accreting	Carse Bay, Caerlaverock (eastern end), Priestside Bank, Wigtown
Open Coast Eroding	Caerlaverock (western end)
Enclosed Bay Accreting	Manxman's Lake, Auchencairn/Orchardton, Southwick
Enclosed Bay Eroding	None

Box 4.2 Current status of the Solway saltmarshes

The four sets are:

- open coast eroding saltmarsh
- open coast accreting saltmarsh
- enclosed bay marsh with no adaptations
- enclosed bay marsh planted with *Spartina*.

Once these preliminaries were carried out the marshes were visited in the field to assess their accessibility and safety. Many saltmarshes have quicksand fronting them and these areas, as far a possible, were avoided. A major consideration had to be the feasibility of transporting field equipment onto the saltmarsh. Those saltmarshes without suitable access points were avoided. Regard was also given to those sites with associated literature which would prove useful for comparison purposes.

The result of this procedure saw four sites on three saltmarshes being investigated as indicated in Box 4.3.

Open coast accreting saltmarsh	Caerlaverock (western side)
Open coast eroding saltmarsh	Caerlaverock (eastern side)
Enclosed bay marsh with no adaptations	Southwick
Enclosed bay marsh planted with *Spartina*	Orchardton

Box 4.3 Study sites

4.2.2 Intra-marsh site selection

From each of the saltmarshes identified through the stratification process (Box 4.3), a study site had to be identified. The saltmarshes cover many hectares effectively precluding a detailed study, therefore it was essential that a smaller area was chosen. An important consideration when choosing such a sub sample is that the results can be applied to the whole site. In order to satisfy rules of inferential statistics, the samples should be homogeneous: an impossible task on saltmarshes due to their extreme variability. Saltmarshes, however, do have a number of common features, for example, creeks, saltpans, a marked front edge, vegetational succession and fronting sand/mudflat. By ensuring the study area within each saltmarsh had these representative features, a degree of comparability could be achieved. These conditions reduced the random element from the sampling to a certain extent. The study sites were, however, randomly chosen, *within* these very loose parameters, maintaining the conditions of sampling as far as is possible in the natural environment.

Once the general location of a site on each saltmarsh was identified, the site was randomly delimited, marking each corner of site with a peg. The location of the pegs was determined using a compass bearing onto some feature on the saltmarsh, for example a prominent fence post, bird watching tower or part of a building (see Figure 4.1). The two inland corner pegs were positioned at some known distance apart and orientated along a compass bearing onto a permanent saltmarsh feature (e.g. a fence post or tree). From these pegs, the two seaward pegs were located, again along a known bearing, for a known distance. Although time consuming, this method of delineating the site ensured the limits of the site would be readily found again, even if the pegs were lost. This method also helped in surveying the site (section 4.5.3). The only disadvantages were that the resultant area was an irregular shape and the size of each area was not the same. These issues did not appear to have consequences for the future analysis of the site.

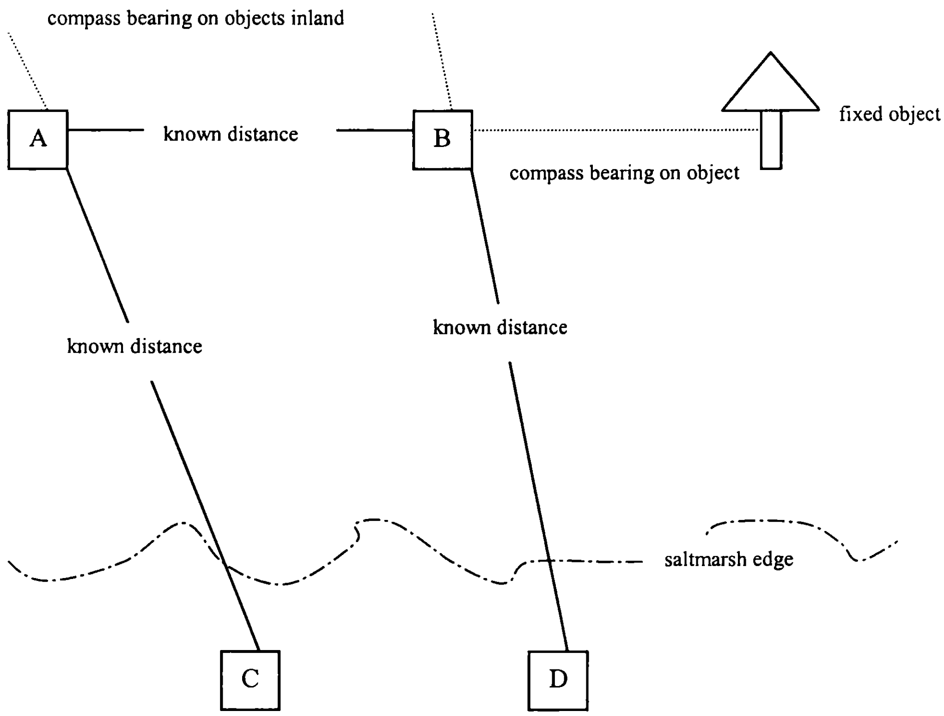


Figure 4.1 Method of delineating study area

4.3 Small scale geomorphological mapping

The above site selection procedure indicates one way in which small scale geomorphological mapping was utilised in this study. A more extensive mapping programme was carried out on all sites sampled using maps from the 1890s (six inch to a mile) and 1970s (1:10 000) to investigate changes in the above saltmarshes over time. The use of historical maps has been used previously in the Solway both on an estuary wide scale (Black, *et al.,* 1994) and on individual saltmarshes (e.g. Marshall, 1960-61, Rowe, 1978, Bridson, 1979, and Pye and French, 1993).

The technique for determining coastal changes and rates of change using maps is well proven and a number of methods have developed for ensuring the procurement of accurate data (e.g. Dolan *et. al.,* 1978, McBride, 1989, McBride *et. al.,* 1991, Thieler and Danforth, 1994).

There are a number of problems associated with the use of archive cartographic material for geomorphological studies. By its very definition, a map will have limitations as it involves a certain amount of generalisation, selective emphasis and conventionalisation (Harley, 1968a). The very earliest maps must be viewed with caution especially with regard to scale and orientation. Even the earliest Ordnance Survey maps, produced in the early nineteenth century are considered much less accurate than their counterparts produced in the late nineteenth century (Harley, 1968b), having been constructed with insufficient funding or guidance. Carr (1962) points to three main problems with the cartographic record and its historical accuracy: technical accuracy, constrained by the sophistication of the instrumentation of the time; misleading cartographic information; and, paper shrinkage subsequent to publication or imprecise copying.

Maps of the coastline have additional problems. Mapping of the coastline was undertaken by both land and hydrographic surveyors in the mid-19th century. The latter were very accurate but the emphasis was placed on navigable channels rather than the whole coastline, whereas the former were more interested in land rather than coastal boundaries. The inadequacy of the mapped coastline was illustrated in 1906 when the Royal Commission on Coast Erosion and Afforestation heard that old maps and charts from the Ordnance Survey Department provided uncertain evidence about changes in the coastline. Carr (1962) suggests that errors in the mapping of the coastline can be attributed to: difficulty in establishing the tide line; a lack of understanding of coastal processes; and errors in the survey. With regard to the first of these, the technical method for determining the mean high water line is to run a level along the coast, measuring the average height of the high tide over a period of 19 years (Crowell, *et al.*, 1991). Since methods have changed over the years the position of the mean high water mark must be treated with caution (Carr, 1962).

The comparison of maps of different ages must be conducted with healthy scepticism. Calculations of the change in coastal features can only be as accurate as the source material from which the data are derived (Crowell, *et al.*, 1991). For example, as well as having less accurate surveys, old historical sheets suffer tears, folds and creases thus reducing the quality of map information. On English maps, the method of calculating tide lines after 1868 differs from maps produced before this date (Oliver, 1993), thus making direct comparison problematic. Fortunately this problem does not occur on Scottish maps, where the use of the high and low water marks of ordinary spring tides have been used throughout. The use of revised, as opposed to resurveyed maps, in map comparison may be flawed because it is hard to tell if areas appearing unchanged in the revision were actually so on the ground (Carr, 1980). Comparison of different aged maps may also be hindered by the introduction of the national grid in late 1930s.

In addition to the problems associated with cartographic quality and accuracy, there lies a problem in comparing map information presented at different scales. After World War Two, the six inch series became the 1:10 000 series. The size of the new maps, therefore, has to be reduced to around 95% of their original size to make direct comparison possible.

This is an easy operation on modern photocopiers, but the map will become distorted and stretched at the edges. The most effective way of establishing the extent of distortion is to locate a straight immobile structure, such as a road or rail track, as a feature of comparison to ensure that the maps are representing those features at the same scale.

Despite the many problems indicated above, the use of archive maps and charts is an effective method for establishing whether change has occurred on the coast. Their utility is summarised by Carr (1980), "Maps and charts have potential value for quantification: they provide a ready means of comparison and permit an immediate visual impact". The crucial points for any researcher to remember is that maps have limitations which must be appreciated before being used (Thieler and Danforth, 1994), and researchers must not try to extract more information from a map than is in fact there (Carr, 1962).

4.4 Large scale geomorphological mapping

One of the study aims is to determine how geomorphology influences the deposition of fine-grained sediment and, in association, radionuclides. In order to achieve this a detailed geomorphological map was essential. This was conducted at a scale of 1:200.

The map for each site was constructed around a series of parallel transect lines, stretching across the study site. The transects were orientated in the same direction as the coast at 10 m intervals and marked with a length of garden twine. A tape measure was extended along each transect line (Plate 4.1). Features intersecting the transect line were measured and marked on the map.

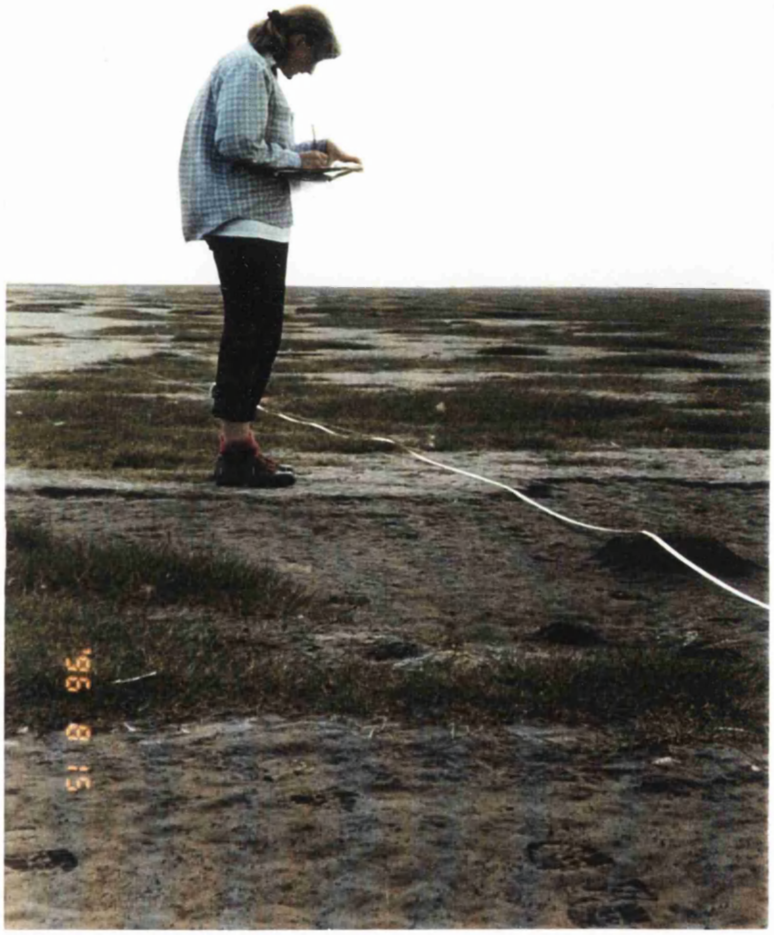


Plate 4.1 Geomorphological mapping

On this basis, the areas between each transect were interpolated by offsets to the positions of features, ensuring their relative positioning was documented as accurately as possible. The accuracy of the resultant map is greatest at the transect lines and diminishes away from the lines. Trial measurements of the position of features showed that the errors in the area between the transect lines were less than 0.5 m which, once drawn on the map, was considered insignificant.

At this stage it is useful to define some terms which will be used to describe geographic areas within saltmarshes in the coming sections and chapters (Table 4.1).

Geographic area/zone	Description
High marsh/upper marsh	This is the landward most part of the marsh, characterised by a wide diversity of vegetation, especially *Juncus maritima, Festuca rubra, Plantago maritima, Limonium,* and *Aster maritima.* This part of the marsh will normally only be inundated at spring tides or during storms.
Middle marsh	This area of the marsh is frequently inundated by the tide and will have a mixed vegetation assemblage, but with a dominance of primary vegetation (e.g. *Puccinellia, Salicornia, Spartina).*
Primary marsh/low marsh	This part of the marsh is frequently inundated by the tide and therefore consists mostly of primary vegetation (e.g. *Puccinellia, Salicornia, Spartina*) with occasional stands of secondary vegetation (e.g. *America maritima).*
Pioneer marsh	This marsh consists only of primary vegetation with *perhaps* isolated stems of secondary species.
Mudflat	This part of the saltmarsh system is generally devoid of vegetation and will be covered by most flood tides.

Table 4.1 Description of terms used to identify saltmarsh zones

4.5 Field measurements of saltmarsh accretion and erosion

4.5.1 Introduction

These studies were conducted firstly, to establish the sedimentologically active areas of the saltmarshes and secondly, to determine their contemporary accretional/erosional status. These data were also necessary to assist in the interpretation of radionuclide distributions in the Solway saltmarshes.

Two methods were employed to measure lateral marsh accretion/erosion. Firstly, the geomorphological map, drawn at the beginning of the study was updated at the end of the study to determine any change. The method used for the re-survey was the same as used for the initial survey (section 4.4). Secondly, two transects on each study site were surveyed annually from a known datum point as described in section 4.5.3.

4.5.2 Plates

Saltmarsh accretion and erosion were measured at a number of points within the study area using buried plates. The plates were made of 3 mm thick aluminium sheet, which were strong enough to resist bending while being inserted into the ground. Each plate measured 20 cm^2 and contained 64 regularly spaced, drilled holes, provided to facilitate free vertical movement of water in the marsh thus avoiding waterlogging and to ensure root development was not inhibited.

The plates were positioned at known intervals along transect lines, enabling them to be relocated. Plates 4.2 and 4.3 illustrate the method employed to insert the plates into the ground. A hole, 1.5 times the area of the plate and of depth about 30 cm, was excavated. The plate was then tapped in a horizontal plane, using a plastic mallet, into the edge of the hole, ensuring the location was noted. The depth to the four corners of the plate was measured using a metal rod (knitting needle), the diameter of which was greater than that of the drilled holes. These four values were recorded and averaged to give the depth of the plate. The excavated hole was carefully re-filled, trying as far as possible to replace all the removed sediment and replace the vegetation turf intact.

No new measurements were taken for several months after insertion, in order to give the plate time to settle into its new position and allow any excess sediment from the excavation to be removed. Time series measurements were taken at the four corners of the plate, re-located by repeatedly inserting the rod until the edges were delimited. Sedimentation rates were determined by averaging the measurement from each corner. The error margin for this method is ± 1 mm, determined by the increments on the tape measure.

Plate 4.2 Preparation for plate insertion

Most of the plates on the accreting marsh sites were easily relocated. In some areas, however, the plate was not located and it is suspected (because of the evidence of recent sedimentation) that the rate of accretion was so great that the rod could not reach the plate. Most of the plates were found by measuring some distance from a marker peg at the edges of the site.

Plate 4.3 Plate insertion

Some of these pegs were, unfortunately, washed away, resulting in the plate being lost. On the eroding site at Caerlaverock, erosion was much greater than first appreciated, resulting in the loss of some plates. Those eroded within the first year were replaced. A few of the plates located on mudflats were also eroded and lost (Plate 4.4).

Plate 4.4 Erosion of sediment on mudflat revealing plate

Excavation of the marsh undoubtedly loosens the soil structure, even if the soil is replaced and packed into the hole. The loss of structure makes the soil susceptible to erosion, with material being entrained by the incoming tide. This action accelerates the erosion on already retreating sites and could initiate erosion on otherwise stable sites (Plate 4.5). Vegetated areas are less likely to suffer from this kind of erosion because the vegetation will protect the damaged soil structure. On a positive note, the erosion of plates acts as further source of information to determine the rate, extent and method of erosion which exists.

Burd (1996) found plates inserted into newly created marsh disintegrated after three years in place. This has not been experienced in the Solway but it may happen in the future.

Plate 4.5 Accelerated erosion of excavated pit

4.5.3 Surveying

Surveying was conducted along two transects at either side of the study site. The starting peg for each of the transects was surveyed to an OS benchmark using a Leica Wild T1010 Total Station. Subsequent surveying was conducted using a Leica Wild NA20 Autoset Level. The level used has an accuracy of 1 mm under perfect conditions but since these are rarely experienced in the Solway, the accuracy is considered to be within 2 cm. This was deemed appropriate for the levelling requirements. The loss of accuracy can be attributed to two main factors. Firstly, the level employs the use of a target staff, which must be kept vertical during measuring. This is often difficult on the exposed and windy Solway coast. Secondly, the staff and the level itself may sink into the ground slightly on very wet ground. As far as possible muddy conditions were avoided, impossible at Orchardton where the whole marsh is muddy. Although the influence of these factors is difficult to quantify, a test can be carried out on the data to establish the level of accuracy. The level requires the reading of three stadia. If taken correctly, the mean of the upper and lower stadial readings should equal the middle reading to within about 1 mm (Leica Heerburg, 1992). Those measurements which did not satisfy this criterion were discarded from the data set.

The survey was carried out with attention to detail, with as many as 70 levelled points on a 150 m transect. All features on the marsh were surveyed, including pans, creeks, drainage rills, clifflets and vegetation changes.

4.6 Sediment sample collection

4.6.1 Sample requirements

Sediment samples were required to establish: a) historical sedimentation rates and, b) the concentrations and distribution of radionuclides within the marsh matrix. In order to establish a comprehensive and accurate spatial and temporal representation of radionuclide distributions, a relatively intensive sampling programme was required within each of the chosen study areas. To achieve adequate spatial covering, ten locations were chosen spanning the lateral extent of each study area and areas representative of particular saltmarsh features, e.g. the edge of saltmarsh creeks, juvenile saltmarsh and the saltmarsh interior. The temporal component required that samples be collected to a depth of approximately one metre in order to capture the Sellafield discharge from which sedimentation rates could be calculated and radionuclide inventories established. The temporal element of sampling will be discussed fully in section 4.7.4.

The sample collection therefore had to adhere to certain criteria:

1. samples had to be accurate representations of the 'in situ' condition of the sediment and remain undisturbed throughout the excavation process (Baxter *et al.,* 1981). Only by avoiding artificial modification by the sampling technique would the stratigraphic, chemical and sedimentological characteristics of the sediment column be retained (Verschuren, 1993);

2. due to the concentration of extraction sites within a small area, collection had to be accomplished in a sensitive manner to preserve the integrity of the study sites. This was especially important on Southwick and Caerlaverock marshes which are protected for their conservation interest.

There are two common methods used for the collection of saltmarsh samples: excavation of sediment from an exposed, vertical surface within the saltmarsh and coring (e.g. Aston *et al.*, 1981; Allan, 1993; Hargis and Twilley, 1994; Hutchinson, 1994). The former of these will be considered first.

4.6.2 Sample collection methods - excavation

Excavation of the saltmarsh can occur in two ways. The simplest is to 'clean' an already existing vertical exposure from a saltmarsh edge, or creek cliff and extract samples from it. This method was improved by Allen and French (1989) with the construction of a sequential sampling frame which provides samples representative of the *in situ* condition of the sediment, but it is only appropriate if there are cliffs available. For example, recent saltmarsh systems may not have experienced the erosional phase which some cliffs can represent. In addition, the location of the cliffs restricts, and introduces bias into, the sampling framework.

Where a pre-existing profile is absent, a pit must be dug into the saltmarsh to create a vertical profile. In order to access sediment to a depth of one metre, the size of pit necessary would be at least 1 m^2. This is extremely destructive, given the number of samples required. Excavation on this scale would lead to older sediment, found at depth, being reintroduced to the upper surfaces of the saltmarsh. This may not only create interpretative difficulties for future investigators but would impede concurrent investigations in the area, such as, investigations into contemporary sedimentation rates. Active saltmarshes with a large hydroperiod would re-adjust relatively quickly to the disturbance of a large amount of sediment but saltmarshes experiencing infrequent tidal inundations may take months, if not years to readjust to damage (Hansom and Leafe, 1990). This method is also very time consuming and may be difficult to execute in sandy sediments (Allen and French, 1989).

4.6.3 Sample collection methods - coring

For the above reasons, it was decided that the most sensitive and practical method for securing sediment samples would be to use a coring device. Coring however, brings with it a number of complications. Wrath (1936) identified two problems: smearing of surface sediment down the length of the core and core compaction. Jackson (1986) expanded on this, including core retrieval, horizon disturbance and sample depth as factors requiring consideration in the use of corers. All of these problems were experienced to some extent and will be discussed in relation to the coring devices tested.

A number of different coring devices were tested and are described below.

1. The Russian corer is specifically designed to collect undisturbed samples whilst avoiding smearing of surface sediments down the length of the core. Unfortunately, while this was suitable for some mudflat sediments, it was impossible to insert the corer into the stiffer and sandier saltmarsh sediments.

2. A manual hammer-driven Farnel corer, as used by Allan (1993) was used to overcome the problem of insertion. The corer has a detachable metal core tube or sheath, 30 cm long and 5 cm in diameter. In order to obtain the required length of core, the corer had to be inserted into the same hole three times. Allan (1993) warned that re-insertion of the corer led to the transmission of sediment from the upper sections of the saltmarsh to the surface of subsequent cores, producing spurious sedimentological and radionuclide results. In order to avoid this a small hole was excavated at the side of the corer and cleaned of any extraneous material. The corer was then inserted into this new hole. However, at the Solway, this solution was found to be as destructive as digging pits into the saltmarsh.

In addition to this problem, the sediment core extracted was substantially shorter than the expected 30 cm, and the method used to extract the sediment from the core sheath proved to be detrimental to the core stratigraphy. Extraction is via a metal plate, situated at the base of the core tube, which is forced down the tube by means of a screw handle, pushing the sediment out as it progresses. This method was not only destructive to the core but compounded the problem of core shortening. The extraction processes and packaging of the core had to be carried out in the field, where the risk of contamination is high. Transportation of the core, while avoiding damage, was also difficult.

The use of this corer highlighted two important points: that a single corer must be used to extract the entire one metre length of sediment required; and, that core shortening, or compaction, is experienced in saltmarsh sediments.

3. The corer ultimately used was a percussion drilling set for heterogeneous soils, produced by Kijkelkamp Agrisearch Equipment. This coring set can sample sediments to an effective depth of 10 metres but in the present study, only one metre was collected. The corer has a hardened steel cutting head, making drilling through the vegetation mat straightforward. A stiff plastic tube, into which the sediment is collected, is inserted into a metal sheath. The inner tube has an external diameter of 50 mm and an internal diameter of 45 mm. Placed at the end of the empty tube is a core 'catcher' to prevent any sediment escaping, which is especially useful for wet sediment. The tube makes transportation of the sample easy and also ensures the sample is not disturbed. The corer was inserted into the ground by a percussion hammer drill, powered by a petrol generator (GX160 Honda 5.5) and removed using a two person operated mechanical rod puller.

This corer solves some of the problems outlined above. It is not destructive, is easily inserted and extracted from the ground, the samples are not disturbed in any way and they are easily transportable. The system, however, still suffers from some compaction of the cores and smearing of surface sediments occurs to a limited degree down the length of the core. These two issues will now be addressed.

4.6.4 Core shortening (compaction)

Despite common use, the term compaction is inappropriate for the phenomenon occurring in the cores. Hillel (1982) defines compaction as "compression of an unsaturated soil body resulting in reduction of the frictional air volume". Another frequently used term is compression which has been used to imply the expulsion of interstitial pore water from the soil body (Cumming *et al.,* 1993). This process would be more accurately described as consolidation (Hillel, 1982) with compression being a term to encompass both the expulsion of air and water. Blomqvist (1985), Cumming *et al.*, (1993) and Wright (1993) all use the generic term core shortening, defined simply as the difference between the depth of sediment recovered and the depth of penetration. This is the term used here. Although generic, the term is preferred because it does not assume the expulsion of either air or water due to the pressure exerted by the action of the coring device.

The use of the above terms suggests that the length of the core is reduced. Loss of core length occurs in both saturated and unsaturated soils. In a saturated soil the amount of interstitial pore space occupied by air pockets, as opposed to water, would not be sufficient to account for the total loss of core length, which can be anything up to 20% of the expected core length. In a moist soil, application of pressure will only expel water once all the air has been removed because of the greater viscosity of water (50-100 times greater than air) (Hillel, 1982). If the interstitial water was expelled (which takes a long period of continuously applied pressure), the stratigraphy evident in the sediment would be destroyed (Wright, 1993). In addition to this Hongve and Erlandsen (1979) noted that the water content within different layers down a sediment core was constant, implying, again, that there was no loss of water due to compression. Therefore, if we assume that there is no expulsion of water and that the pore space occupied by air is insufficient to account for the loss of core length, there must be another explanation for the core shortening.

Hongve and Erlandsen (1979) attributed core shortening to friction between the lining of the corer and the sediment. The friction exercises pressure below the mouth of the corer which results in downbending and stretching of the sediment layers. By this mechanism the stratigraphy remains intact but each layer is thinned. Continued pressure to the base of the core may result in plugging: a phenomenon especially common in long cores (Lanesky *et al.,* 1979, Blomqvist, 1991)

The degree of core shortening is influenced by a number of factors. The recovery of sediment reduces with decreasing diameter of corer (e.g. Hongve and Erlandsen, 1979, Martin and Miller, 1982) and the amount of shortening can be reduced if entry into the sediment is rapid (Hongve and Erlandsen, 1979). In sub-aqueous samples, Blomqvist

(1991) suggests slow penetration into the sediment to prevent the loss of surficial sediments, while Gerwitz (1977) states that compaction is not a function of the time taken to for the corer to penetrate.

4.6.5 Problems associated with the correction of core shortening

Effective correction of core shortening is, at best, problematic, given the inconsistent amounts of shortening occurring in apparently similar sedimentary conditions. Morton and White (1997) suggest that shortening or distortion of cores during extraction is likely to be more prevalent than the existing literature would suggest, because of the difficulty in quantifying and rectifying the distorted core. There are two main issues: when does shortening of the core begin; and, do all parts of the core experience shortening to the same extent?

With regard to the first of these issues, Gerwitz (1977) notes that shortening is zero at a depth of 0-30 cm for sediment with a medium water content. Blomqvist (1985) also suggests that shortening is absent in the surface sub-aqueous sediments due to the saturated, flocculent nature of the tested sediment and, that the depth at which shortening commences is positively correlated to the diameter of the core cylinder. In contrast, Crusius and Anderson (1991) imply that the tops of gravity cores are compressed because the friction acting on the sediment begins as soon as the corer enters the sediment.

There is also debate concerning the extent of shortening along the core and whether some sediments are more prone to shortening than others. Lebel *et al.* (1982) state that core shortening is a linear function of the depth of core penetration by the corer in compact mud and stiffer clays but non-linear relationships have been found in soft bottom sediments. (Blomqvist, 1985). Wrath (1936) noted that sediments at depth are less 'compacted' than those at the surface. Despite these apparent down-core relationships, Hongve and Erlandsen (1979) suggest that shortening may have different effects on different sediment layers, with the poorest recovery coming from soft layers deposited between stiffer layers and that recovery of both sediment types decreases with depth. Blomqvist (1991) noted that clayey silty sediments are shortened more than light unconsolidated organic sediments. Lanesky *et al.* (1979) state that plugging of the core can occur when a layer of sand or peat overlies less resistant muddy material. Bloom (1964), in an assessment of natural compaction (due to sediment overburden), suggests that 'compaction' is highly variable as a result of different types of sediment, indicating that shortening due to mechanical processes will also be highly variable.

From these studies, three questions arise:

1. when does shortening commence?

2. how does core shortening vary as a function of depth?

3. does the process of thinning vary between different sediment layers?

4.6.6 Core shortening as a function of penetration depth and commencement of shortening

This was investigated on Caerlaverock saltmarsh, mid way through a tidal cycle, ensuring that the sediment was moist but not saturated. Most of the sample cores were taken under these conditions. A number of cores of different lengths were taken on the mudflat and upper saltmarsh. Five core depths were taken in each location: 18 cm; 38 cm; 58 cm; 80 cm; 100 cm. The shortening occurring in each was measured and plotted as a function of the depth of core penetration (Figure 4.2).

The graph shows clearly that the extent of core shortening is constantly related to the depth of corer penetration (R^2 = 0.997) with the regression line passing through the origin (at 99% confidence limit). It can, therefore, be concluded that shortening will begin the instant the corer enters the sediment and that the extent of shortening will be linear down the length of the core. Given the compatibility of the results from the upper saltmarsh and the mudflat, it can be assumed that all the cores taken from areas between these two extremes will adhere to this relationship. This conclusion agrees with those of Crusius and Anderson (1991) and Lebel *et al.* (1982) and with comments by Blomqvist (1985).

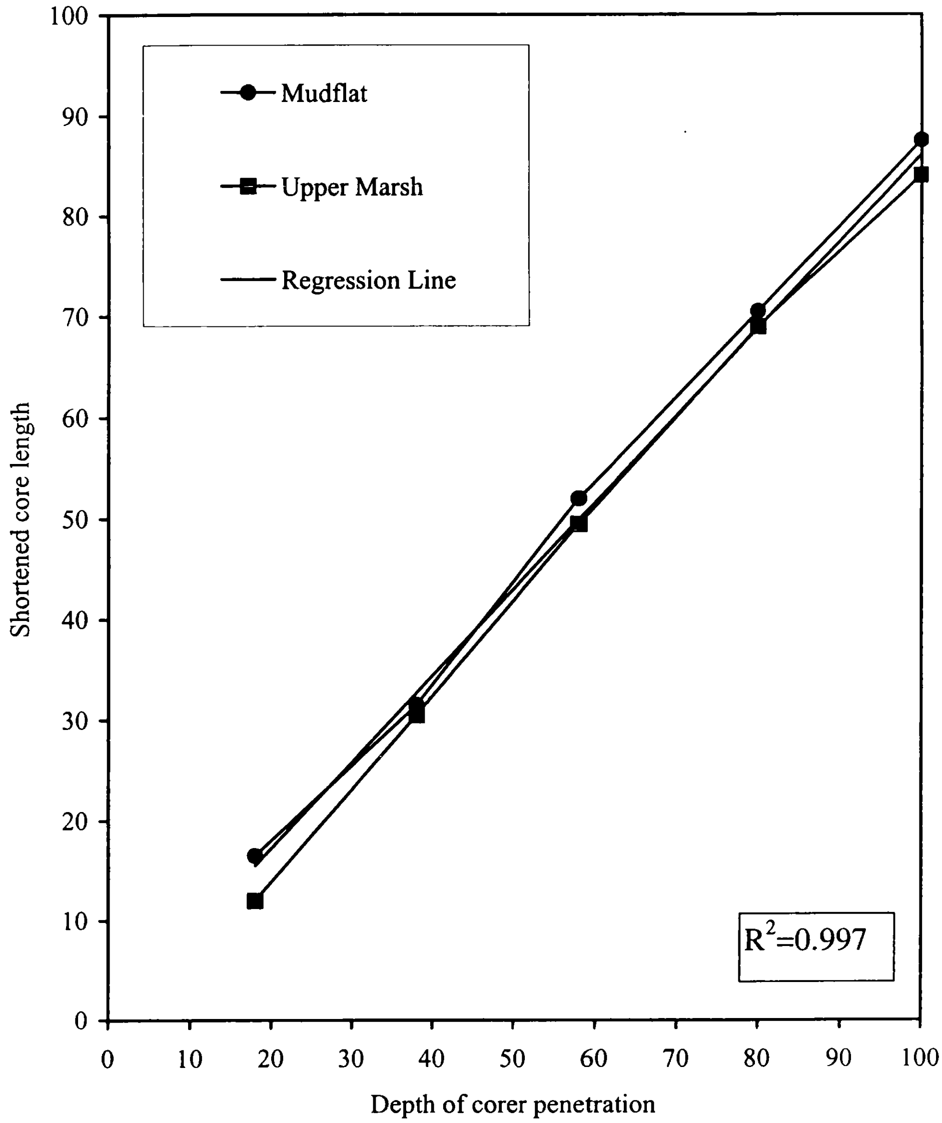


Figure 4.2 Relationship between depth of corer penetration and extent of core shortening

4.6.7 Variability of shortening within different sediment layers

This was investigated in a qualitative manner by comparing distinctive marker horizons from two adjacent cores, extracted consecutively, for a number of locations within Southwick saltmarsh. The core locations are presented in Table 4.2. The hypothesis is that once the shortening is corrected for, a marker horizon in adjacent cores should be at the same level, if there is no variability of shortening within different sediment layers. It is assumed that the linear relationship discussed above would not only be valid for the core as a whole but for each individual stratigraphic horizon.

Core	Location
SWA	Mudflat
SWB	Mudflat, 8 m from marsh cliff edge
SWC	Middle marsh, 2 m from the edge of a small creek
SWD	Primary/middle marsh, bank of largest creek
SWE	Inner bend of largest creek meander
SWF	Middle marsh, 2 m from bank of largest creek
SWG	As above, 20 m upstream from SWF
SWH	Middle marsh next to small creek
SWJ	Middle marsh distant from creeks or pans
SWK	Upper marsh, 2 m from pan system

Table 4.2 Location of cores on Southwick marsh

The compaction is accounted for by using the simple equation:

$$\textbf{Corrected factor} = \textbf{100} \div \textbf{shortened length}$$

This correction factor is then used to calculate the corrected length of each marker horizon.

Table 4.3 indicates that whilst all are close, only one of the marker horizons exactly coincide (SWF). Variation in the extent of shortening between the paired cores can be attributed to differences in the speed at which the corer was inserted into the ground.

The variation in shortening between different horizons can also be assessed visually by measuring the width of corresponding horizons in the paired cores. In many cases the width of the two horizons differs slightly, with the variation being larger in organic-rich, silty layers than in inorganic, sandy layers. This observation agrees with that of Morton and White (1997) and Blomqvist (1991). However, the variation which exists between each pair of marker horizons is, in the majority of cases, less than 2 cm. We can therefore state that any horizon within the core will be within two centimetres of its original position.

Core	Shortened length (cm)	Shortening factor	Horizon 1		Diff. (cm)	Horizon 2		Diff. (cm)	Horizon 3		Diff. (cm)
			Orig.	Readj.		Orig.	Readj.		Orig.	Readj.	
SWA (a)	77.5	1.29	44	56.8	-1	49	63.2	-5.7			
SWA (b)	70.5	1.42	41	57.8		48.5	68.9				
SWB (a)	84	1.19	9	10.7	0.1	35.5	42.2	5	59	70.2	-1.8
SWB (b)	85	1.18	9	10.6		30.5	36		61	72	
SWC (a)	88.5	1.13	16	18.08	-0.73	41	46.3	-0.4	70	79.1	-0.1
SWC (b)	87.5	1.14	16.5	18.81		41	46.7		69.5	79.2	
SWD (a)	89	1.124	12.5	13.5	-0.5	51.5	57.9	-0.7	71	79.8	-0.1
SWD (b)	89.5	1.117	12	14		52.5	58.6		71.5	79.9	
SWE (a)	87.5	1.14	6.5	7.4	1.2	42	47.9	2.1	75	85.5	0.2
SWE (b)	88.5	1.13	5.5	6.2		40.5	45.8		75.5	85.3	
SWF (a)	88.5	1.13	6	6.8	0	14.5	16.4	0	53	59.9	0
SWF (b)	88.5	1.13	6	6.8		14.5	16.4		53	59.9	
SWG (a)	91.5	1.09	7	7.6	-0.5	36	39.2	-0.8	66	71.9	-1.7
SWG (b)	93	1.08	7.5	8.1		37	40		67.5	73.6	
SWH (a)	84.5	1.18	10	11.8	-1.2	46	54.3	-0.9	61.5	72.6	-0.1
SWH (b)	80.5	1.24	10.5	13		44.5	55.2		58.5	72.5	
SWJ (a)	90	1.11	20	22.2	-2.4	29.5	32.7	-2.6	44	48.8	-0.1
SWJ (b)	89	1.12	22	24.6		31.5	35.3		44.5	49.8	
SWK (a)	94.5	1.06	6	6.4	0.5	35.5	37.6	-1.3	60	63.6	-1.7
SWK (b)	92.5	1.08	5.5	5.9		36	38.9		60.5	65.3	

Table 4.3 Unadjusted and adjusted positions of marker horizons in Southwick cores

4.7 Preparation of cores

4.7.1 Opening the core tube

The core was removed by slicing the wall of the tube lengthways using a 35 mm circular saw (127 mm diameter blade). The core tube was secured to a holding frame designed to ensure that the saw did not quite cut fully through the core tube. This thin layer of intact tube was then cut using a sharp blade (Stanley carpet cutter) thus minimising disturbance of the sediment.

4.7.2 Smearing

The cores, when first opened did not display any sedimentological features because of a film of fine mud across the surface. This smearing is caused by the dragging of sediment along the core tube wall or the mixing of material between adjacent sections (Chant and Cornett, 1991). This can occur in two ways: as the core penetrates the sediment; and, as the core is being extruded from the core tube (although smearing in this case was not caused by this action). Smearing can distort the calculation of sedimentation rates (Chant and Cornett, 1991) or affect the determination of the mobility of elements through sediments (Anderson *et al.,* 1987).

In order to counteract this, Wrath (1936) suggested drying the core and scraping off the outer surface to remove the 'skin' of smeared material, while Baxter *et al.* (1981) sectioned the cores prior to the removal of the sediment.

Of these solutions, the former was used. The smearing in this case was caused primarily by the clawing action of the core catcher as the corer was inserted into the ground. The teeth of the catcher penetrated the sediment by only 2-3 mm, distorting the sediment within this thin layer. This thin layer of sediment was removed from the surface, leaving the undisturbed central section of core.

4.7.3 Core logging

Each core was logged, taking note of the major sedimentological characteristics revealed after removal of the smeared layer. This was done simply to maintain a record of the sedimentology of the core before sectioning. Notes were taken on the extent of shortening, colour and texture of the sediment and the extent of root penetration.

4.7.4 Sampling of cores

Previous studies in the Solway, e.g. Allan (1994) and Ben Shaban (1989), used core sections measuring between 2 cm and 5 cm for radionuclide investigations in the Solway, but no sampling strategy was discussed. It was considered that for the purposes of this work, a more detailed sampling strategy was required in order to accurately determine sedimentation rates using the Sellafield radionuclide signature. A value of 2 cm was chosen, reflecting the minimum sedimentation rates calculated in previous studies at Southwick (MacKenzie *et al.*, 1994) and the extent of internal variation within the cores as a consequence of core shortening.

This extremely detailed data set provided the opportunity to assess whether a larger sampling increment would display the same gross patterns in radionuclide data as the fine resolution sampling. The 2 cm sample increments were integrated mathematically to simulate cumulative sections of 4 cm, 8 cm and 16 cm and compared graphically. Three examples of these graphs are illustrated in Figures 4.3 - 4.6 but the observations are similar for all the Southwick cores. In most of the graphs, the 16 cm integrated increment displayed the gross patterns (in this context, the existence or absence of a sub-surface maxima) shown by the 2 cm increments. In all graphs, the 8 cm increment displayed the gross patterns. This suggests that, if only gross patterns are required for interpretation of the radionuclide data, increments of between 8 and 16 cm would be acceptable. This sampling strategy was subsequently adopted for Caerlaverock Marsh, thus saving a large amount of sample preparation and analysis time.

4.7.5 Sample preparation

Each of the samples, once cut from the core, was prepared using the method indicated in Box 4.4.

1. Samples weighed wet
2. Samples oven dried for 24 hours at 70°C
3. Samples reweighed
4. Samples disaggregated, stored in plastic bags and labelled

Box 4.4 Sample preparation

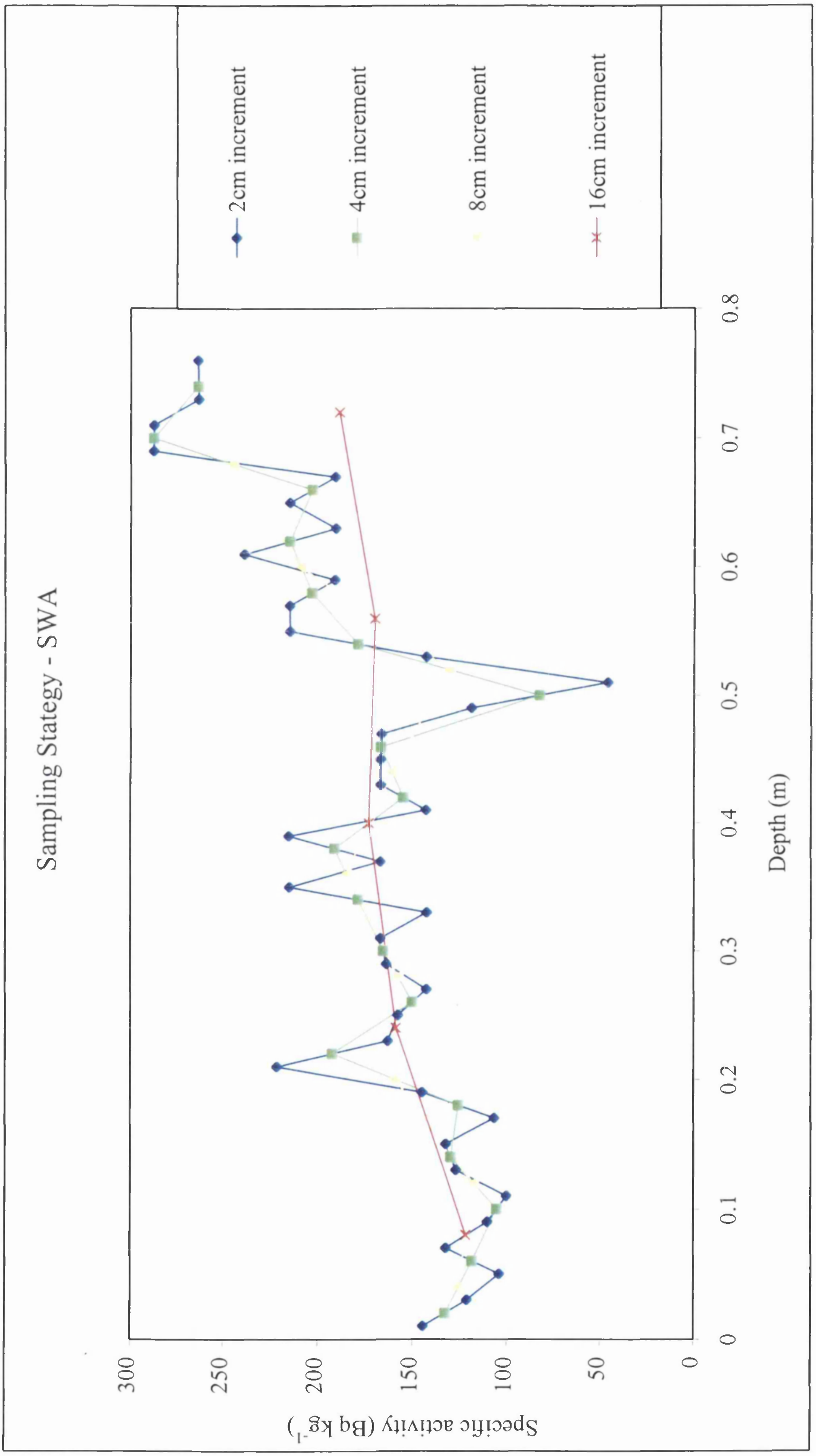


Figure 4.3 Sampling strategy – Core SWA

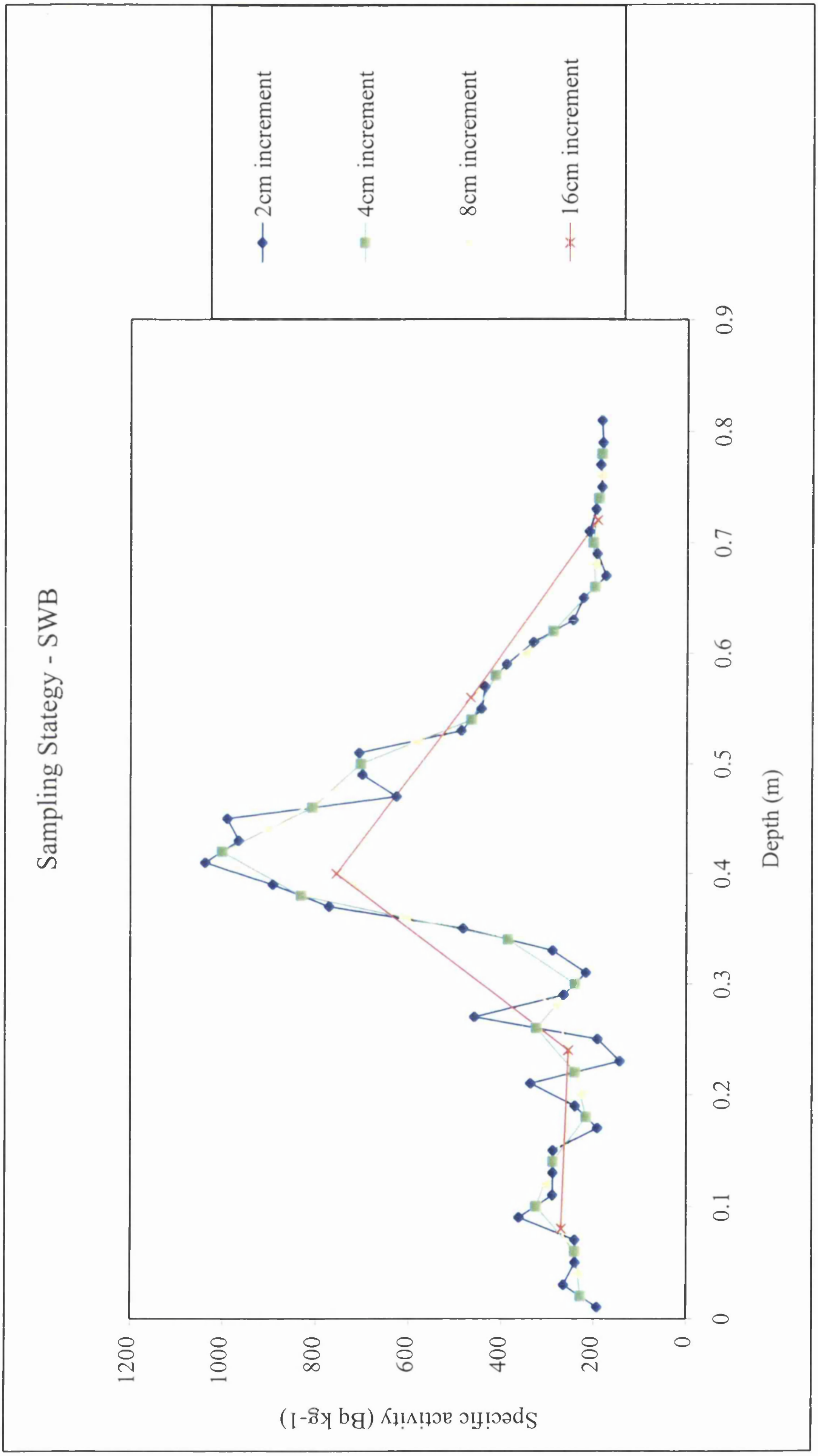


Figure 4.4 Sampling strategy – Core SWB

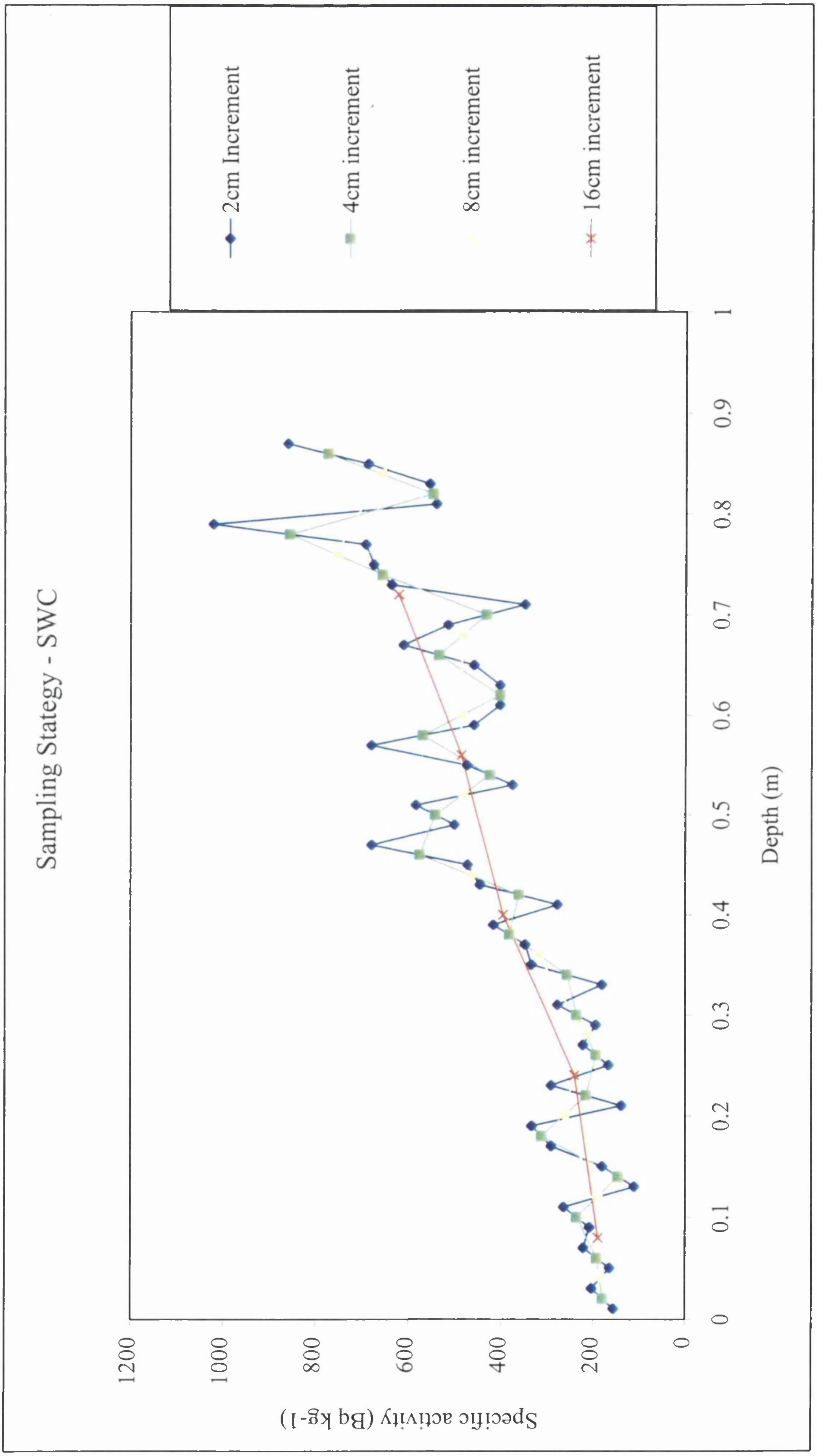


Figure 4.5 Sampling strategy – Core SWC

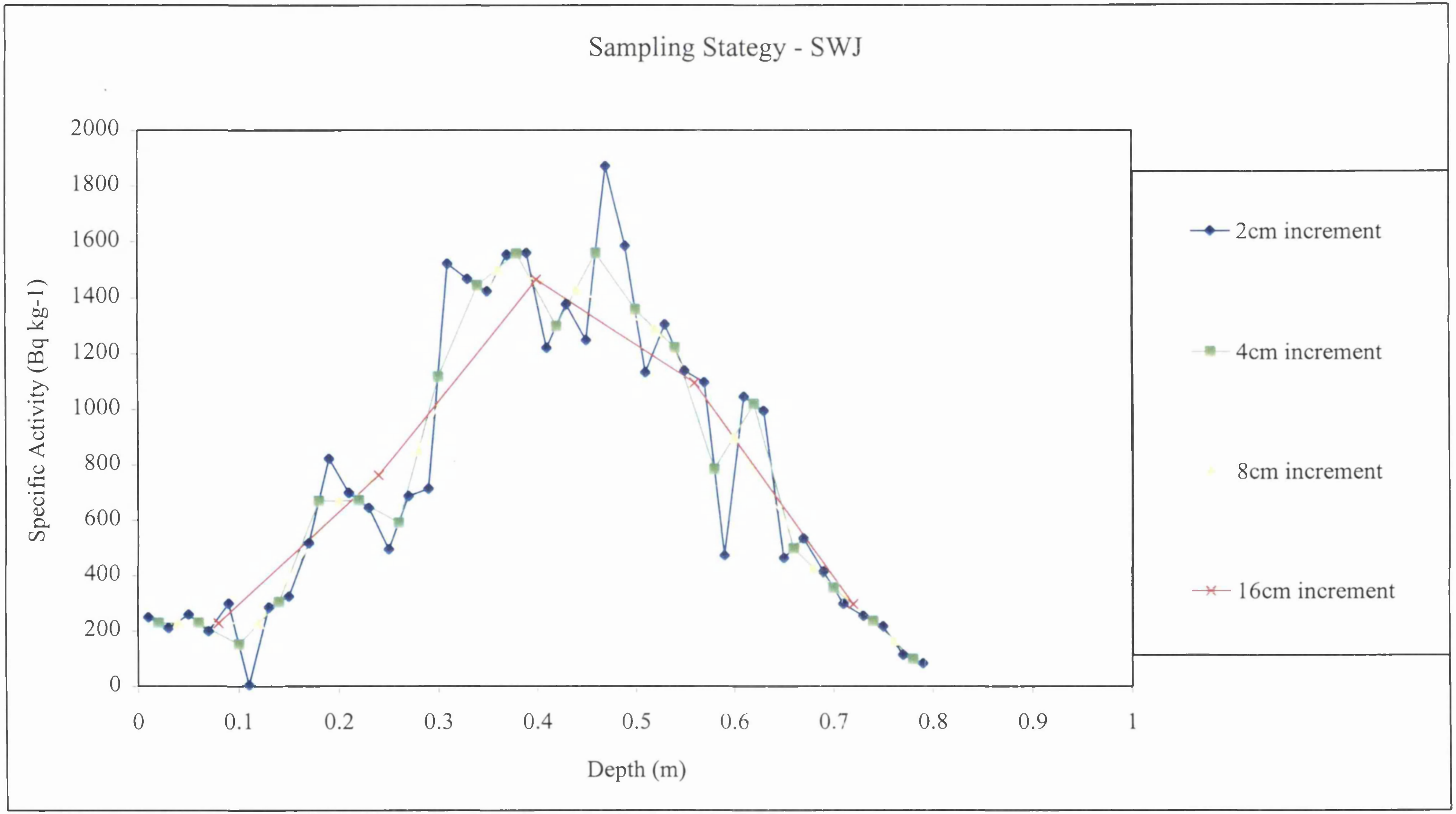


Figure 4.6 Sampling strategy – Core SWJ

4.8 Sedimentological characteristics

4.8.1 Determination of organic content

The organic content is an important property to determine, given the important functional role of organic matter in binding radionuclides (e.g. Pulford *et al.,* 1998) Various methods for determining organic matter exist, but the most common is the estimation of organic content by loss on ignition. This involves oxidising the organic carbon in air by heating and determining the weight loss of the sample (Brimblecombe *et al.,* 1982). Although a simple method, care must be taken not to ignite the sediment at too high a temperature to avoid loss of CO_2 from carbonates and for this purpose Gale and Hoare (1991) recommend that ignition should be performed at a temperature of 430°C. The method used to assess the organic content is described in Box 4.5.

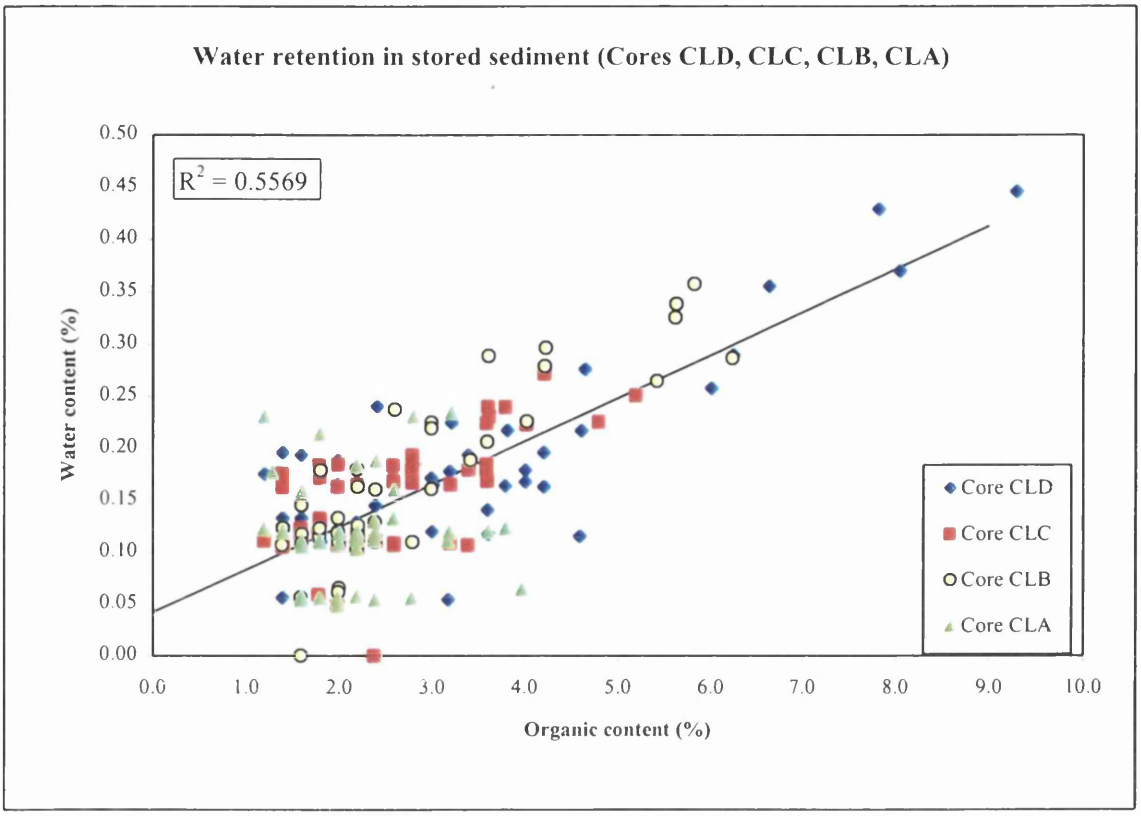
The importance of removing moisture prior to weighing (step 4) was tested using four cores from Caerlaverock Marsh, representing varying components of the marsh. Gale and Hoare (1991) suggest that the mass of dry samples exposed to the air will increase as samples equilibrate with the laboratory humidity resulting in an overestimation of organic content. The amount of moisture in the sample will depend on the organic and clay mineral content of the sample. Certain clay minerals are able to absorb water actively unlike quartz grains which will experience little surface adsorption. The amount of water adsorption by clays depends on features such as the crystal size and lattice arrangement: montmorillonite has a large adsorption capacity; illite, an intermediate capacity and; kaolinite, a low capacity (Marshall and Holmes, 1979). Four cores, with varying amounts of organic material and mineral content, were used to determine the moisture content of the dry sediment. The influence of organic content was directly measured but the effect of sediment mineralogy could only be estimated using the core logs constructed prior to drying.

The crucible and sediment were weighed before, and after, being oven dried to determine the extent of water loss. Water loss was expressed as a percentage of the pre-dried sediment weight. The cumulative results for the cores are shown in Figure 4.7. The plot of all four cores gives a positive correlation between water loss and organic content, with an R^2 value of 0.5569 (n = 180). The plot of three cores, minus CLA, gives an R^2 value of 0.6463, a more convincing relationship. The influence of core CLA on the reduction of the coefficient of determination (R^2) is shown in Figure 4.8. There is no apparent relationship between the organic content of CLA and the amount of water retained in the dry sediment. This could be explained by examining the mineralogy. Core CLA was extracted from the sandflat fronting Caerlaverock marsh, the sediment of which is largely coarse, quartz sand with limited fine grained material. It would, therefore, appear that a lack of clay minerals will preclude water adsorption, even if organic material is present. Cores CLB, CLC and CLD were all taken from the marsh which has layers of fine/organic material.

1. Crucible oven dried to remove moisture from porous clay
2. Crucible weighed
3. Approximately 5g of disaggregated sediment added to crucible
4. Crucible and sediment oven dried for at least one hour at 100°C to remove air moisture
5. Crucible and sediment weighed to 2 decimal points
6. Crucible and sediment placed in furnace at 430°C for 24 hours
7. Crucible removed and placed in desiccator to cool
8. Crucible and sediment weighed
9. Weight loss calculated as a percentage of the oven dry sample weight.

Box 4.5 Determination of organic content

This test illustrates that sediments containing clay minerals and organic material will absorb air moisture during storage. It is, therefore, imperative to remove this before trying to assess the organic content.



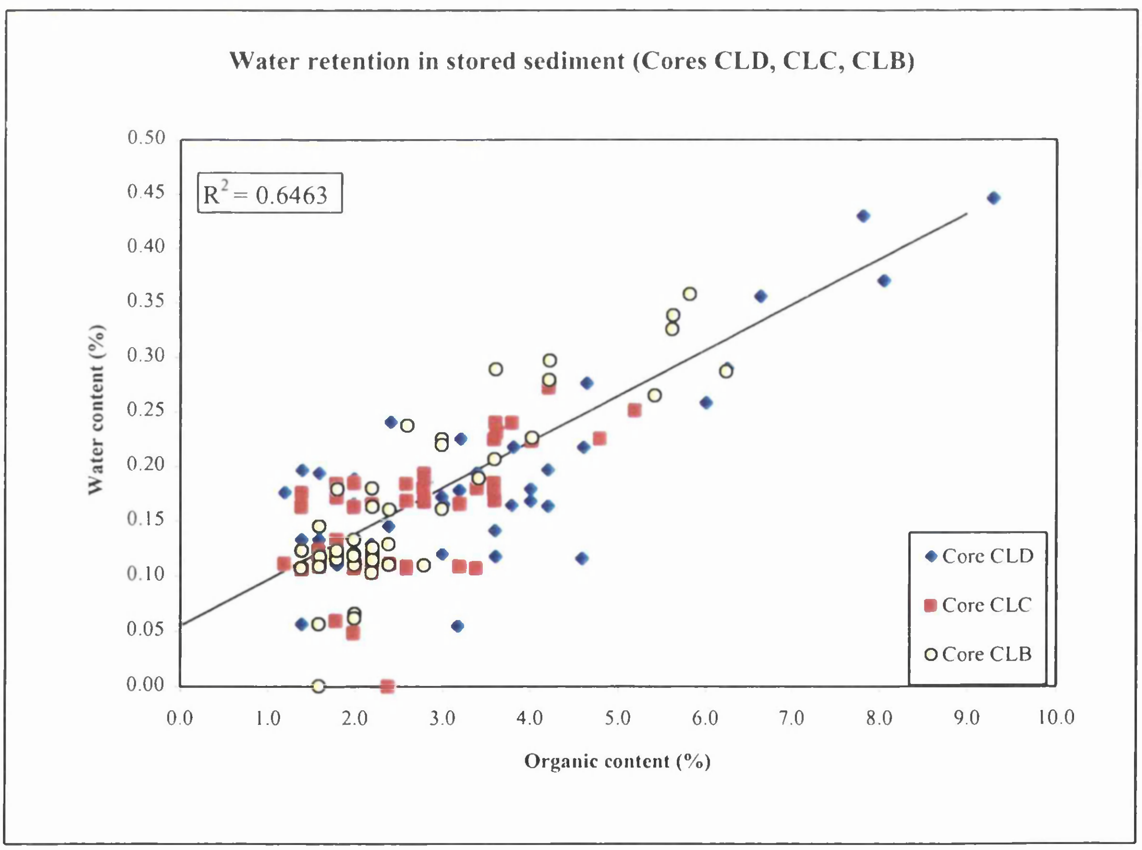


Figure 4.7 Water retention in stored sediment (cumulative results)

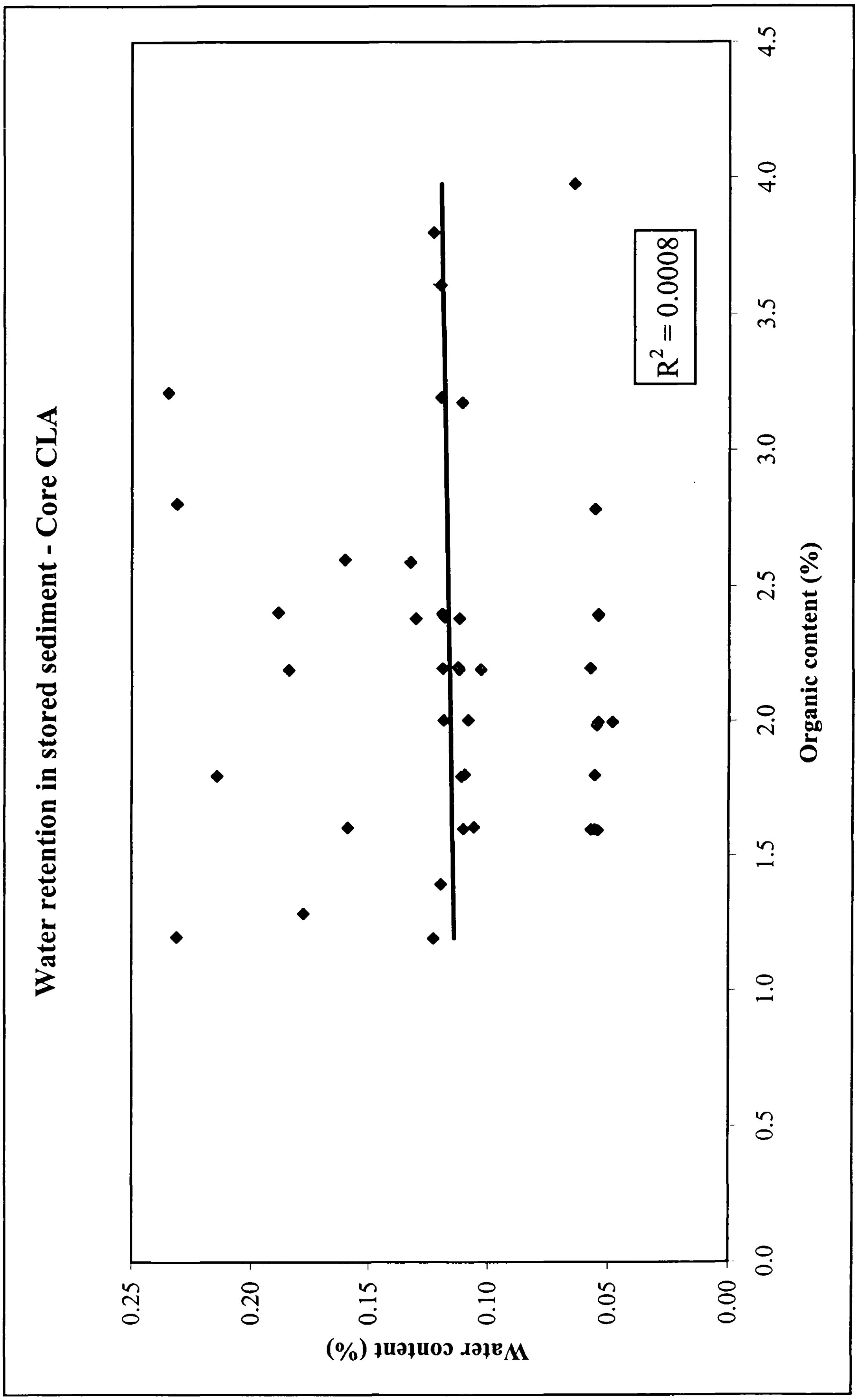


Figure 4.8 Water retention in Core CLA

4.8.2 Sediment size analysis

Numerous authors have indicated an inverse relationship between sediment size and radionuclide concentrations, both in subaqueous (e.g. Aston and Duursma, 1973; Miller *et al.*, 1982; MacKenzie *et al.*, 1987), and subaerial (e.g. Jones *et al.*, 1984) sediments. Jones *et al.* (1988) concluded that the sea bed sediment type influences the radionuclide concentration and that the sediment type is itself shaped by historic and contemporary sedimentary regimes. This statement also holds true in subaerial sedimentary systems. It is important therefore, to establish both the character of the marsh sediments and the extent of their influence on the distribution and concentration of radionuclides.

Two methods were used in the analysis of sediment grain size. Dry sieving determined the sand and coarse silt fraction, while the silt and clay fraction was analysed by laser diffraction.

4.8.3 Dry sieving

Each sample was sieved through four mesh sizes: 500 µm; 250 µm; 125 µm; and 63 µm. Dry sieving is only suitable for sediments above 63µm (coarse silt). Below this, electostatic attraction between the particles restricts material passing through the sieves (Gale and Hoare, 1991). Each sieve stack was mechanically shaken for 10 minutes. The cumulative percentage by weight for material coarser than each sieve size was calculated. The mass percentage of material lost during the procedure was also calculated. Gale and Hoare (1991) suggest that if this amount exceeds 0.5% of the initial sample, the results should be ignored.

The material collected by the sieve stack pan was used for further particle size investigation by laser diffraction. Samples for laser diffraction have to be pre-treated to remove any aggregated particles and dispersed to prevent flocculation. The sediment was dispersed overnight in a solution of 100 ml distilled water and 25 ml Calgon* stock solution. The sample solution was vigorously shaken to ensure full dispersal. The use of

* The stock solution was prepared using 35 g sodium hexametaphosphate and 7 g sodium carbonate in 1 l of distilled water, as recommended by BS 3406.

sodium hexametaphosphate was recommended as a dispersal agent in marine sediments by Hetherington and Jeffries (1974).

4.8.4 Laser diffraction grain-size determination

4.8.4.1 Principles of laser diffraction

Investigation of the < 63 μm sediment fraction of the sample was conducted using a Coulter LS230 Variable Speed Fluid Module. This analyser works on the principle that particles of a given size diffract light through a certain angle that is inversely proportional to the particle size. The intensity of the diffracted light also varies with particle size, with a high intensity equating to large particles. Only about 10% of the laser light* is diffracted by particles as the light passes through a sample cell. The remainder is focused on to a beam dump. The diffracted light, which extends over a wide range of angles if the sample has a large variation in particle sizes, is focused by two Fourier lenses on to an array of 127 detectors. The lenses ensure that light which is diffracted by particles of the same size, and therefore have identical diffraction angles, is diffracted towards the same detector. The detectors in the Coulter LS230 are able to detect particles of sizes 2 mm - 0.4 μm. Below this size, the angle of diffracted light is higher than the highest detector.

To measure particle sizes below 0.4 μm, the Coulter LS series uses a PIDS system (Polarisation Intensity Differential Scatter). The PIDS system systematically measures the light scatter at two perpendicular polarisation angle (vertical and horizontal), for three wavelengths at six angles of detection. The difference in intensity measured at the two polarisation angles is the PIDS signal and this is used to determine particle sizes between 0.1 and 0.6 times the wavelength of the incident polarised light. The three wavelengths used are 450 nm (blue), 600 nm (orange/red) and 900 nm (near infra-red), allowing the analysis of particles between 0.04 μm and 0.54 μm (Coulter, 1997).

* The light source is a class IIIb solid state diode laser with a wavelength of 750nm.

4.8.4.2 Optical Models

The analysis of the diffracted light, both in conventional laser diffraction systems and using PIDS, requires a model to interpret the pattern of scattered light. The simplest and most commonly used model is based on the Fraunhofer theory and is concerned simply with the diffraction of light around a particle (Hoff and Bott, 1990). This theory is only applicable to spherical particles greater than 10 μm and is inaccurate below 5 μm (Bayvel and Jones, 1981). Below this size, the scattered light patterns are more complex, involving, not only the diffraction of light, but light reflection and refraction. The theory which includes all aspects of light scattering is the Mie theory, the calculations for which depend on the wavelength of the light beam, the refractive index of the particle and the refractive index of the medium in which the particle is suspended (Hoff and Bott, 1990). The Coulter LS230 has the capacity to use either the Fraunhofer model or a Mie-based model based on the optical properties of the sediment being analysed. In samples which include a substantial amount of sub-micron material, it is essential that the Mie theory is used.

The optical model used to analyse the Solway sediments was determined using the relative mineral compositions assessed from a series of X-ray diffraction photos (from Allan, 1993). The properties of the model are shown in Table 4.4.

Wavelength of light beam	750 nm
Refractive index of medium	1.33
Refractive index of particle "real"/ordinary "imaginary"/absorptive	0.01

Table 4.4 Optical Model properties

The particle refractive index contains two parts: the "real" or ordinary part and the "imaginary" or absorptive part. The "real" index is the refraction of light as it passes from the suspending material into the particle. The "imaginary" index is the attenuation of light as it passes through the particle. The former of these properties is published for many common minerals so an appropriate value can be calculated based on the composition of the sample. The "imaginary" index must, however, be estimated. Hoff and Bott (1990) state that results will vary slightly if the value of the parameter varies by 3-10, and provide a table of absorption value ranges (reproduced in Table 4.5).

The appropriate value to use is, of course, determined by the particles evident in the sample. For example, Muggler *et al.* (1997) used adsorption values of 0.15 (for the 750 nm laser wavelength) and 0.2 (for the polarised wavelengths) for use on kaolinite rich weathered soils. Loizeau, *et al.* (1994) used a "negligible" value for sediments of fluvial and lacustrine origin. As shown in Table 4.3, the value used for the Solway sediments was 0.01, reflecting the high proportion of quartz in the sample.

TYPES OF MATERIALS	ABSORPTION VALUES
clear materials - glass, clear polymers	< 0.001
latex, translucent materials, quartz, polymer resins	< 0.01
lightly coloured translucent materials	0.01-0.1
metal oxides, highly coloured materials	0.1-1.0
metallic particles, carbon, or other black materials	1-10

Table 4.5 Absorption value ranges

The effect of different optical models on the analysis of the Solway marsh sediments was tested on three different samples from a core (SWK) taken from Southwick Merse. This core was used for all test runs on the machine. Each of the three samples was analysed using the Fraunhofer theory and the compiled marsh optical model. The results are shown in Table 4.6.

The Fraunhofer model slightly overestimates the size of the coarse fraction but substantially underestimates the size of the fine fraction. This emphasises the importance of using a Mie-derived optical model to interpret sediment with a clay component.

Sample	Model	Mean sample size (μm)	% Difference	>5% sample size (μm)	% Difference	>95% sample size (μm)	% Difference
SWK 16/18 cm	Fraunhofer Marsh	43.24 43.93	**-2.3**	81.93 81.70	**0.3**	1.374 2.003	**-45.8**
SWK 2/4 cm	Fraunhofer Marsh	48.27 48.31	**-0.1**	86.66 86.22	**0.5**	2.176 2.358	**-8.4**
SWK 4/6 cm	Fraunhofer Marsh	52.91 53.66	**-1.4**	91.74 91.57	**0.2**	3.849 6.021	**-56.4**

Table 4.6 Use of different optical models

4.8.4.3 Obscuration

In addition to an appropriate optical model, correct assessment of the sample requires the density of the sample suspension to lie within certain limits. The suspension density range, known as the "obscuration index" is determined by the machine. The obscuration should be 8%-12%, with a PIDS obscuration of 45%-55% (Coulter, 1994). In samples with a high clay content, the PIDS obscuration may be adequate at 50% but will only yield an overall obscuration of 2-3% resulting in a loss of sample accuracy for particles larger than 4 μm. If this low obscuration is compensated for by adding more sample, the PIDS obscuration may become too high, blocking the PIDS system (Buurman *et al.*, 1997). This problem will usually only occur when there is more than 50% clay sized particles. The average obscuration and PIDS signal for the Solway sediments were 6-8% and 45-55% respectively, thus ensuring an accurate assessment of all particles sizes.

4.8.4.4 Instrument reproducibility

An important consideration when using any analytical tool is whether the instrument is measuring samples the same way each time. There are two internal checks made by the Coulter LS230 to ensure reproducibility which are done automatically ever hour the machine is in use. The first, determines the output from the detectors when the laser is turned off. These offsets are measured and used to readjust the final detector output figures.

The second, checks the alignment of the laser in relation to the detector array. Any change in the alignment will result in the scatter pattern being observed at the incorrect angle producing errors in the subsequent interpretation of the pattern. The method of alignment in the Coulter LS series gives an overall alignment error of less than 1% (Cooper, 1996).

Before each sample run, the machine also measures the background illumination of the suspension fluid and the overall system. A background scatter pattern could be caused by contaminants in the suspension fluid (tap water) and/or dirt on the lenses. Subsequent sample analysis is adjusted to take into account the background scatter.

The machine reproducibility was tested using a number of samples from core SWK. Each sample was run through the analyser three consecutive times, with no rinsing of the machine between each run. The mean sediment size, > 5% sample and the > 95% sample were compared to assess the accuracy of the machine. This test was repeated for on 6 different samples and the results are shown in Table 4.7.

The first run sequence was conducted with the machine pumping the sample through the analyser at full speed. The analysis shows an increase in the size of the coarse fraction (>95% sample) from 79.84 μm to 127.9 μm but only a tiny change in the fine fraction. This suggests that the fast speed of the pump creates bubbles in the system which are being detected as large particles. Subsequent runs used a pump speed of 50% to mitigate against this.

The standard deviation for the coarse fraction of the samples (> 5%), excluding the first sample, varies from 0.06 μm to 0.17 μm. For the fine fraction (> 95%), the standard deviation varies from 0.003 μm to 0.04 μm. Given that the standard deviation of the coarse fraction is close to the detection limits of the machine and the fine fraction is lower than the detection limits, it was deemed that the machine was reproducing the results within acceptable limits.

Sample	Mean sample size (μm)	Mean value (μm)	Standard deviation (μm)	>5% sample size (μm)	Mean value (μm)	Standard deviation (μm)	>95% sample size (μm)	Mean value (μm)	Standard deviation (μm)
SWK 16/18a									
run 1	34.7			79.8			0.80		
run 2	38.1	**38.9**	**3.8**	94.2	**100.6**	**20.1**	0.81	**0.82**	**0.02**
run 3	43.9			127.9			0.84		
SWK 16/18b									
run 1	43.2			81.9			1.37		
run 2	43.0	**43**	**0.18**	81.7	**81.73**	**0.14**	1.37	**1.37**	**0.003**
run 3	43.0			82.0			1.37		
SWK 16/18c									
run 1	48.5			88.3			1.94		
run 2	48.3	**48.3**	**0.17**	88.1	**88.13**	**0.12**	1.92	**1.92**	**0.02**
run 3	48.1			88.1			1.90		
SWK 2/4b									
run 1	51.6			89.4			3.03		
run 2	51.5	**51.47**	**0.01**	89.2	**89.22**	**0.11**	2.99	**2.989**	**0.04**
run 3	51.4			89.1			2.94		
SWK 2/4c									
run 1	49.8			88.6			2.41		
run 2	49.5	**49.59**	**0.12**	88.2	**88.39**	**0.17**	2.38	**2.38**	**0.02**
run 3	49.5			88.3			2.36		
SWK 2/4d									
run 1	49.8			88.6			2.56		
run 2	49.8	**49.83**	**0.05**	88.5	**88.57**	**0.06**	2.55	**2.548**	**0.01**
run 3	49.9			88.6			2.53		

Table 4.7 Machine reproducibility

4.8.4.5 Operator reproducibility

Changes in the analysis conditions can be caused by the operator as well as the machine itself. The operator must ensure that the sample being tested is representative of the sample as a whole and that the method of sample selection is the same for all sample runs. Both these requirements were tested by analysing a number of samples removed from one sample bottle. The test was carried out on three different sample bottles with eight samples being removed from each bottle. The results of this test are given in Table 4.8.

Sampling material in suspension can be problematic because larger particles will invariably sink to the bottom of the bottle. This means that the sample will contain a higher proportion of fine grained particles than is representative of the whole. This problem is alleviated because the sediment has been sieved to below 63 μm. To reduce the problem even further, the particles were kept in suspension while the sample was removed. This was achieved by placing a magnetic bar* in the sample bottle and placing it on a magnetic stirring plate. The bar spins, mixing the solution and preventing the coarse sediment from settling. This method of maintaining the suspension was used in preference to sonication (which the machine can implement before or during the sample run) which was found to create bubbles and so distort the results. Once in suspension, a sample was removed from the bottle by pipette, adapted to ensure that the sample from each bottle was taken from the middle, close to, but not touching, the bottom.

Sample	Mean sample size (µm)	>5% sample size (µm)	>95% sample size (µm)
SWK 24			
a	48.3	86.7	2.18
b	51.6	89.4	3.03
c	49.8	88.6	2.41
d	49.8	88.6	2.56
e	51.4	89.3	2.96
f	48.1	87.7	2.11
g	48.7	87.7	2.25
h	48.9	88.0	2.19
Mean value	**49.5**	**88.2**	**2.46**
Standard deviation	**1.2**	**0.8**	**0.34**
SWK 46			
a	52.2	91.7	3.85
b	51.3	91.1	3.24
c	51.3	91.1	3.14
d	52.2	91.8	3.26
e	51.7	91.6	3.09
f	51.6	91.8	3.02
g	52.0	92.2	3.05
h	50.6	91.4	2.78
Mean value	**51.6**	**91.6**	**3.18**
Standard deviation	**0.5**	**0.3**	**0.29**
SWK 1820			
a	42.5	83.5	1.92
b	40.9	82.7	1.77
c	41.0	82.3	1.77
d	40.1	82.1	1.69
e	40.8	82.3	1.74
f	41.7	83.4	1.76
g	42.2	83.7	1.80
h	40.8	82.9	1.70
Mean Value	**41.2**	**82.8**	**1.77**
Standard deviation	**0.8**	**0.6**	**0.07**

Table 4.8 Operator reproducibility

* The magnetic bar attracts a negligible amount of sediment.

The results show that, on the whole, the standard deviation of the results was less than 1 μm for the coarse fraction and less than 0.5 μm for the fine fraction and are therefore acceptable for the purposes of this work. There are problems in the retrieval of suspended sediments, partly due to the test itself. The size distribution of sediment within the sample bottle will change every time a sample is removed. This cannot be remedied as it is impossible to put the sample back into the bottle once it has run through the machine.

4.9 Radionuclide analysis of cores

4.9.1 Background information

Radionuclides are essentially nuclides which have an unstable nucleus due to an excess of either protons or neutrons. If unstable, the nucleus will spontaneously change in the direction of greatest stability, losing energy in the process. This is known as radioactive decay. The amount of energy lost (Q) by a specific radionuclide during radioactive decay is always constant (Figure 4.9).

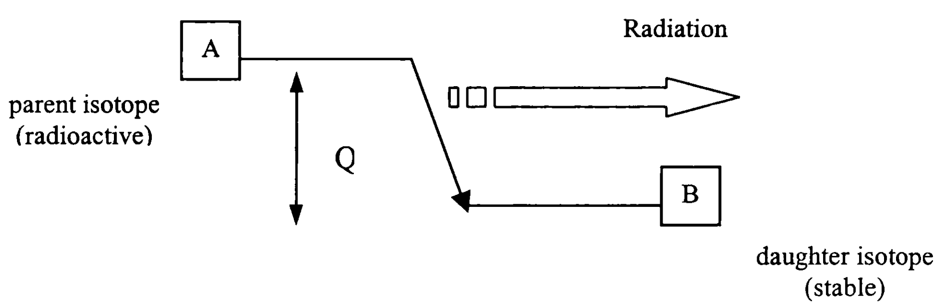


Figure 4.9 Energy loss through radiation

Energy released is in the form of kinetic energy or electromagnetic energy. Radioactive decay may be distinguished on the basis of the particles emitted by which the nucleus will achieve stability. The different types of decay are:

- alpha (α) decay
- beta (β) decay
- gamma (γ) decay
- spontaneous fission

- proton decay emission of heavier particles such as ^{14}C (Keller, 1988).

The route towards nucleus stability may involve one or more of these decay processes. The simplest way in which the nucleus can reach a more stable state is by emitting a γ-ray which usually rapidly follows some other nuclear event such as the emission of an α- or β- particle (McKay, 1971). γ- rays, emitted from a specific radionuclide, have a specific energy characteristic of the nuclide. This property can be used as a tool for identifying nuclide species.

4.9.2 Gamma Spectrometry

Gamma spectrometry is used to measure the energy (measured in electron-volts, eV*) of the γ- rays being emitted from a particular source, thereby allowing identification of the radionuclide species responsible.

Almost all devices for detecting radiation use the ionisation produced in different sensitive absorbing materials to produce an electrical pulse which can then be recorded, amplified, counted and sorted electronically (McKay, 1971). The number of individual radioactive disintegrations counted by the detector can be displayed as photopeaks, associated with the energy levels of the radionuclides within the source material. For example, the existence of ^{137}Cs and ^{241}Am are identified by photopeaks at 662 keV and 59.9 keV, respectively.

In this work two such devices were used for detecting the γ- emissions from ^{137}Cs and ^{241}Am: both are co-axial N type High Purity Germanium (HPGe) Detectors manufactured by Canberra Industries and Tennelec. The basic principles of each machine are the same, and both are controlled by the same computer software.

An important consideration in the use of such devices is the efficiency with which the detector will pick up the energy signature, a quality dependant on the interaction of the radiation with the machine. The manner in which γ- rays are absorbed in material is

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* The electron volt unit is also used to express the kinetic energy of moving particles such as alpha particles, protons, neutrons etc., and is equivalent to the kinetic energy acquired by a single electron in being accelerated through a potential difference of one volt (Cole, 1988).

extremely complex and involves three different mechanisms, each of which depends upon the energy of the incident radiation and the nature of the material through which it is passing (Cole, 1988). Of all the particles leaving a particular radioactive source, only a proportion will reach the detector 'counter': some are absorbed by materials on the way; some travel in the wrong direction, and in the case if γ-rays, some may pass through the absorbing materials with no effect (McKay, 1971). The absolute efficiency of HPGe co-axial detectors varies with energy (EG&G ORTEC, 1994), therefore the detector efficiency will be different for ^{137}Cs and ^{241}Am: the latter having the highest detection efficiency due to a lower energy. The efficiency can be expressed as thus:

$$\text{Detector efficiency} = \frac{\text{observed counting rate}}{\text{source disintegration rate}} \times 100\%$$

Another factor affecting the efficiency of the detector is the geometry and the material of the sample being analysed. For example, samples of the same mass but different materials will occupy different volumes, therefore changing the efficiency of the detector. A thick sample will be less efficient because the γ rays will have more material through which to travel (Figure 4.10).

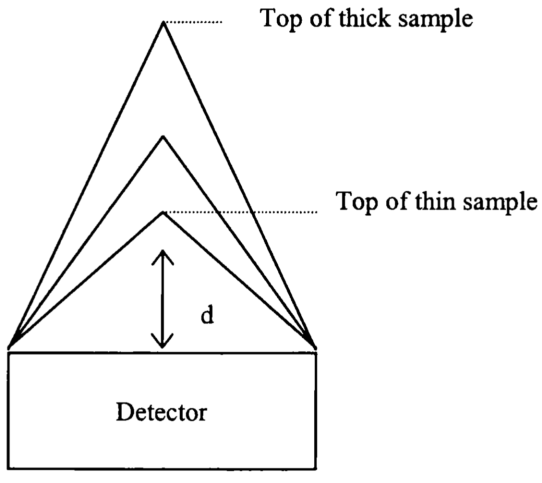


Figure 4.10 Effect of sample geometry on detector efficiency

The efficiency of the detector was established by 'spiking' some saltmarsh sediment (analysed to ensure it contained no detectable radionuclides) with a known activity of ^{137}Cs and ^{241}Am, a process carried out for each detectors used.

In all cases, including the analysis of the standard, the sediment used and the geometry of the sample was kept as similar as possible. Each sample (prepared as per procedure in Box 4.4) was carefully measured for 20g and placed into the detector for a period up to 24 hours, or until a counting error of $\leq \pm$ 5% was achieved (as recommended by Clifton and Hamilton, 1982). In most cases, this level of error was achieved within 2 hours of analysis.

In addition to establishing the efficiency of the detector, the background activity, resulting from stray radioactivity, cosmic rays and defects in electrical circuits (McKay, 1971), was determined. Precautions against background activity can be taken by shielding the detector (in the case of the Portable Canberra and the Tennelec by approximately 10cm of lead) and using construction materials which are free of radioactivity.

4.9.3 Calculation of specific activities and errors

The procedure used to calculate the specific activities of the saltmarsh samples is outlined in Box 4.6.

1. Determine the specific activity (in Bq kg^{-1}) of the standard. Decay correct the standard for ^{137}Cs. This need not be done for ^{241}Am because of its long half life.

2. Determine the efficiency of the detector being used, using the standard. The error of the efficiency should also be calculated.

3. Calculate the activity of each sample, correcting the value by introducing the efficiency. Calculate the error of the sample activity. Quote all final values as Bq kg^{-1}.

Box 4.6 Method used to calculate radionuclide specific activity

The calculation for the specific activity of sample is outlined in Box 4.7.

1. Calculate net counts per second (CPS) = CPS $_{(sample)}$ – CPS $_{(background)}$

2. Calculate the activity by taking into account the detector efficiency:

$$\frac{\text{Net CPS}}{\text{efficiency}} \times 100$$

3. Convert into Bq kg^{-1}

$$\frac{\text{total no. of Bq in sample}}{1} \times \frac{100}{\text{weight of sample}}$$

Box 4.7 Calculation of sample specific activity

5. RESULTS

5.1 Southwick

5.1.1 Setting and historical development

Southwick Merse is located within the Inner Solway Firth around grid point NX 95 91 55. The entire Inner Solway has been designated a Special Protection Area under the EC Directive for the Conservation of Wild Birds (79/409/EEC), a Ramsar site, under the International Convention of Wetlands of International Importance, and has also been proposed as a Special Area of Conservation under the EC Habitats Directive (92/43/EEC) (Solway Partnership, 1998). Southwick Merse is bisected by Southwick Water, which, in spite of a very small fresh water inflow, is characterised by a large channel depth and width. The north western part of the site is owned and managed by the Scottish Wildlife Trust (SWT) and the eastern part is run by the Royal Society for the Protection of Birds (RSPB). The sample site on this marsh at the north-western side of the marsh was chosen primarily because of ease of access and to allow comparisons with previous studies (Allan, 1993, Ben-Shaban, 1989). The marsh is classified, using the criteria presented in Chapter three, Figure 3.9, as North European, macro-tidal, estuarine marsh, with natural *Puccinellia* vegetation grazed by wildfowl.

The marsh nestles at the base of the Criffel Granite, a large granodiorite pluton associated with which are a series of mineralised uranium veins (MacKenzie *et al.*, 1991). The base of Criffel has been washed by successive global sea level rises, the most recent occurring during the early Holocene. Landforms modified during this sea level rise are evident in the form of a raised sea arch (the Needle's Eye) and sea stack (Lot's Wife). Investigation of the merse has shown the sediments to contain dinoflagellate cysts and foram linings of Holocene age, although the deep marsh sediments may be older (Hooker, 1991).

Successive maps from 1854 and 1980 were compared to assess the extent of change which has occurred in the marsh. Development over the last 150 years has been controlled to a large extent by the position of Southwick Water and reclamation of the land for grazing purposes (Figure 5.1).

The 1854 map shows that the land adjacent to Southwick Water as far as the tidal limit is merse (saltmarsh) whereas the most recent map shows this as rough ground indicating an increased marsh elevation and reduction in tidal flooding. In addition, the position of the tidal limit in the most recent map is approximately 200 m seaward of the 1854 position. The channel of Southwick Water from the tidal limit to Needle's Eye appears to have narrowed through time with marsh encroachment onto the banks of the channel. There is, however, little difference indicated on the successive maps in the position of the marsh between Needle's Eye and Lot's Wife.

The maps illustrate some 20 m of marsh fronting Lot's Wife to the south. This marsh however has experienced substantial accretion and currently extends some 100 m south from Lot's Wife. Further marsh advancement is now limited by the position of Southwick Water. The study site is contained within this most recent part of the marsh, as illustrated by the arrow in Figure 5.1.

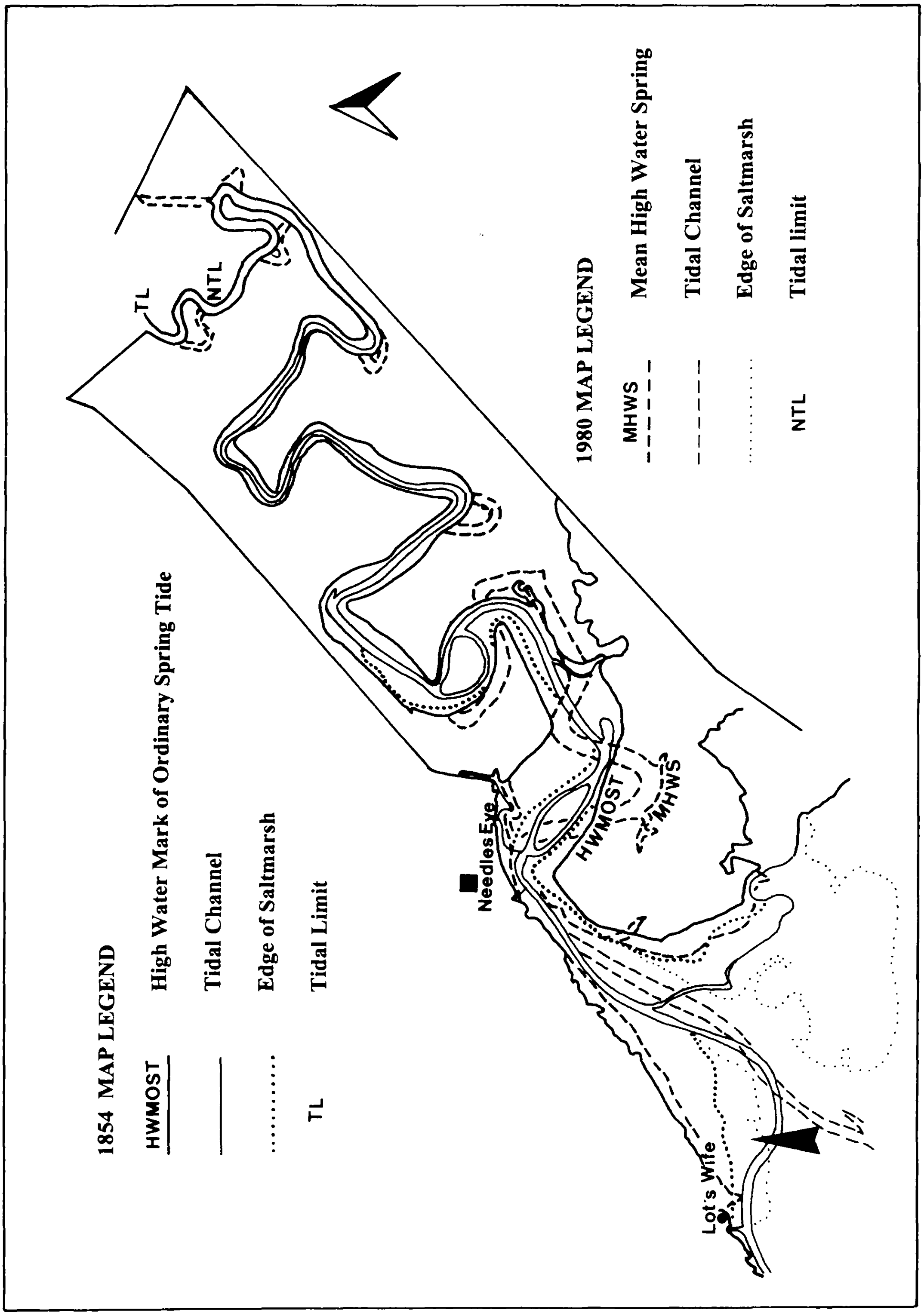


Figure 5.1 Compilation of 1:10 000 maps from 1854 and 1980 demonstrating extent of change on Southwick Merse (arrow indicates study area)

5.1.2 Geomorphology, vegetation and recent changes in the study site

A map of the geomorphology of the study site is shown in Map 1a (contained in map folder) and a map of the vegetation and recent changes is shown in Map 1b (map folder). The study site occupies an area of approximately 7705 m^2, within which there are a number of tidal creeks, saltpans, and marsh cliffs. There are three distinctive parts to the study area: high marsh; middle marsh and primary marsh.

5.1.2.1 Primary marsh

The primary marsh is colonised by *Puccinellia* with smaller amounts of *Salicornia* and *Glaux maritima.* The marsh here is not fully vegetated and there is as much as 40% bare mud. Towards Southwick Water the vegetation becomes even more sparse until, after a distance of 10 m to 15 m, it is totally absent and 100% bare mudflat slopes towards the waters edge.

Occupying the north-eastern part of the primary marsh is a steep marsh cliff of approximately 1 metre height. Above the mudflat surface the cliff face is colonised by vegetation and does not appear to be actively eroding. The character of the cliff changes further upstream with the cliff dominating the front part of the marsh and reaching several metres in height. In addition, where there is no fronting mudflat, the cliff acts as the bank to Southwick Water.

5.1.2.2 Middle marsh

The middle marsh area extends northwards from the primary marsh for approximately 70 metres. The dominant vegetation is *Puccinellia maritima* and *Salicornia*, with lesser amounts of *Glaux maritima* and *Aster tripolium.* There are also many isolated stands of *Halimione portulacoides* and *Plantago maritima.*

While only one saltpan exists in this part of the marsh, there are many small areas which are pan-like in appearance and are colonised by species more tolerant of saline conditions. These areas have a higher percentage of *Spartina*, *Puccinellia* and *Salicornia.* They are generally wetter underfoot and are mostly found at the head of small creeks and rills. These topographically lower areas collect water from the surrounding marsh which then drains into the creeks. The edge of this area is again marked by a distinct change in the dominant vegetation.

5.1.2.3 High marsh

The landward-most part of the high marsh is colonised by the brackish water species, *Phragmites.* The *Phragmites* stands reach over 1.5 metres in height and occupy bare mud, with no ground covering vegetation. This part of the marsh is inundated only during the highest spring tides, therefore the *Phragmites* represents the transition from saltmarsh to terrestrial vegetation. In front of the *Phragmites* for a distance of some 30 metres, the area is densely vegetated. Dominant species in this area are *Juncus maritima* and *Festuca rubra,* with varying amounts of *Plantago maritima, Limonium vulgare, Aster tripolium, Triglochin maritima, Armeria maritima* and small amounts of *Puccinellia maritima.*

Saltpans are found predominantly in the high marsh area. These pans remain filled with seawater even at low water and this has precluded the development of vegetation. As a result the floors of the pans are bare with only a small amount of vegetation around the rim. Those which are vegetated are colonised by *Puccinellia maritima* and *Salicornia*, although in the last year of the study period, some of the pans had also become colonised by *Spartina*. The vegetated pans are still noticeable because of differences in the vegetation between the pan area and the surrounding marsh, i.e. the pan has more primary vegetation. The edge of the high marsh is marked by a small relict marsh edge discernible by a small dip in the topography and a significant change in the dominant vegetation type.

Inundation of the marsh surface occurs as Southwick Water becomes filled with tidal floodwater and fills the smaller channels in the marsh which then overbank. Some parts of the marsh are inundated only by the smaller creeks but others are inundated both by these and directly by Southwick Water. Higher parts of the marsh are inundated only during the highest astronomical tides (HAT), but even during smaller tides, these areas become wet underfoot because of the rise in the groundwater levels.

The dimensions of the largest creek in the study area change as it meanders towards the marsh edge and the sea. The greatest channel width in the study area is 9 m, with a depth of 1.3 m. The banks of the creek are prone to failure by undercutting and rotational slipping during periods of high water pressure. For example, in some parts, the creek banks have been undercut by the flooding and ebbing tide and have slumped by 60 cm. The width of the channel (at its widest part) between the two slumped banks is 4 m. The width of the creek narrows to 2 m towards Southwick Water and the depth reduces to 70 cm. The change in channel dimensions is a function of marsh maturity with the marsh upstream being older and therefore higher. The smaller creeks vary in width but are all between 50cm and 1m deep. Some of the creeks are infilling with sediment and are becoming colonised with *Spartina.*

There has been little change in the drainage pattern of the marsh in the three years of the study period although the pattern of vegetation has altered and there is now more *Halimione* and *Plantago* in the middle marsh area. *Spartina* is encroaching on the saltmarsh and, despite attempts to curb its growth (Plate 5.1), seems to be flourishing. Colonisation of the mudflat by primary vegetation has advanced towards Southwick Water but the location and topography of the fronting marsh cliff has remained the same.

Plate 5.1 Evidence of chemical spraying in an attempt to subdue *Spartina* growth

5.1.3 Sedimentation in the study area

By inserting metal plates below the marsh surface and measuring the distance from the plate to the ground surface, the rate and pattern of sedimentation across the marsh was determined. The plate positions are shown in Map 1a. The full results of this study are given in Appendix 1, Table (i), as are the calculated sedimentation rates, recorded as mm y^{-1}. A summary of the results is given in Table 5.1. The calculated rates range from -5.3 cm y^{-1} to 9.3 cm y^{-1}. The values found on opposite banks of a creek (4 and 5a and 8 and 9) were very similar and, given that they are inundated for the same length of time, such a result suggests that this method of determining sedimentation rates works well. A few of the plates however, could not be relocated because, either the sedimentation was so high that the measuring instrument could not reach the plate, or the location of the plate had been mis-recorded, or the plate had washed away. With regard to the first of these possible reasons, it difficult to find an appropriate longer instrument which was both strong enough to push through the marsh sediment without flexing and small enough to avoid undue disturbance of the soil.

Plate	Position on marsh	Sedimentation rate ($cm\ y^{-1}$)
1	High marsh	2.2
2	High marsh	1.3
3	Middle marsh	2.9
4	Middle marsh - nr. creek	1.9
5a	Middle marsh - nr. creek	2.1
5b	Middle marsh	2.0
6	Middle marsh	1.6
7	Middle marsh	3.4
8	Middle marsh - nr. creek	2.7
9	Middle marsh - nr. creek	2.6
10	Middle marsh - nr. creek	1.7
11	Middle marsh	2.6
12	Slumped creek bank	8.6
13	Slumped creek bank	2.7
14	Middle marsh	4.6
15	Middle marsh - nr. creek	6.3
16	Middle marsh - nr. creek	2.2
17	Middle marsh	2.8
18	Inner bend of creek meander	*
19	Inner bend of creek meander	*
20	Middle marsh - nr. creek	9.3
21	Middle marsh	5.1
22	Pioneer marsh - *Puccinellia*	*
23	Mudflat	2.1
24	Mudflat - nr. channel	-5.3
25	Mudflat - nr. channel	2.3
26	Mudflat	*
* unable to calculate (see text)		

Table 5.1 Summary of Southwick plate results

The sedimentation rates on the high marsh are variable. Plate 1, positioned between two creeks is flooded infrequently (although it is inundated directly from Southwick Water, the main tidal channel at Southwick), has a rate of 2.2 cm y^{-1}. Plate 2, 6 m from the nearest creek has a lower rate of 1.3 cm y^{-1}.

The middle marsh results also exhibit a wide variety of sedimentation rates. Those plates in the middle marsh which are positioned at some distance from creeks have rates of 2.9 cm y^{-1}, 2.0 cm y^{-1}, 1.6 cm y^{-1}, 3.4 cm y^{-1}, 2.6 cm y^{-1}, 4.6 cm y^{-1}, 2.8 cm y^{-1} and 5.1 cm y^{-1}, (Plates 3, 5b, 6, 7, 11, 14, 17 and 21 respectively). There appears to be a general increase in rates towards the front of the marsh, for example, Plates 6, 17 and 21, located progressively closer to the front of the marsh, have progressively higher rates. The pattern however, is not conclusive.

Most of the plates located on the middle marsh proximal to creeks have rates equivalent to those at a distance from the creeks. Plates 4 and 5a have rates of 1.9 cm y^{-1} and 2.1 cm y^{-1} and, further downstream, Plates 8 and 9 have rates of 2.7 cm y^{-1} and 2.6 cm y^{-1}. Variable rates are found associated with the largest creek in the study. Rates of 8.6 cm y^{-1} and 6.3 cm y^{-1} are exhibited by Plates 12 and 15 situated directly on the channel bank. Plates 10 and 16, situated above the slumped banks of the creek have lower rates of 1.7 cm y^{-1} and 2.2 cm y^{-1}. Plate 13, however, which is located on the creek slumped bank also has a lower rate of 2.7 cm y^{-1}. Plate 20 situated downstream of these points has a rate of 9.3 cm y^{-1}, the highest rate experienced at this marsh.

The mudflat accretion rates have a wide range with Plates 23 and 25 exhibiting accretion rates of 2.1 cm y^{-1} and 2.3 cm y^{-1}, while Plate 24 has an erosion rate of -5.3 cm y^{-1} possibly due to its proximity to a small meandering tidal channel.

The results broadly indicate that the highest sedimentation rates occur towards the front of the marsh and adjacent to creeks. Excluding the negative value, the lowest sedimentation rate, occurs at the rear of the marsh, 6 m from the nearest creek.

5.1.4 Profiles of the study area

Two transects were surveyed within the study site. The locations of the transects had to be chosen with care so that the exact positions could be resurveyed over successive years. In order to achieve this, the marked boundaries of the study site were used for the transects. It was hoped that these surveys would illustrate changes through time in the level of the marsh, but at the scale of survey there were no determinable differences in the successive survey results and therefore these have not been considered further.

5.1.5 Determination of organic content of sediment within marsh sediments

In order to determine the contribution of organic material to the sedimentation of the marsh, a number of cores were taken from the marsh, the locations of which are indicated in Map 1a. A summary of the location of each core is given in Table 5.2.

Core	Location
SWA	Mudflat
SWB	Mudflat, 8 m from marsh cliff edge
SWC	Middle marsh, 2 m from the edge of small creek
SWD	Primary/middle marsh, bank of largest creek
SWE	Inner bend of largest creek meander
SWF	Middle marsh, 2 m from bank of largest creek
SWG	As above, 20 m upstream from SWF
SWH	Middle marsh next to small creek
SWJ	Middle marsh distant from creeks or pans
SWK	Upper marsh, 2 m from pan system

Table 5.2 Core locations on Southwick

Each core was divided into 2 cm vertical increments and analysed for organic content as indicated by the percentage loss on ignition (% LOI). The results of these analyses, given as percentages, are in Appendix 1, Table (ii) and the summary statistics are shown in Table 5.3. Graphs of each core profile are presented in Figure 5.2. The range of values across the whole site is from 1 % to 8.3 %.

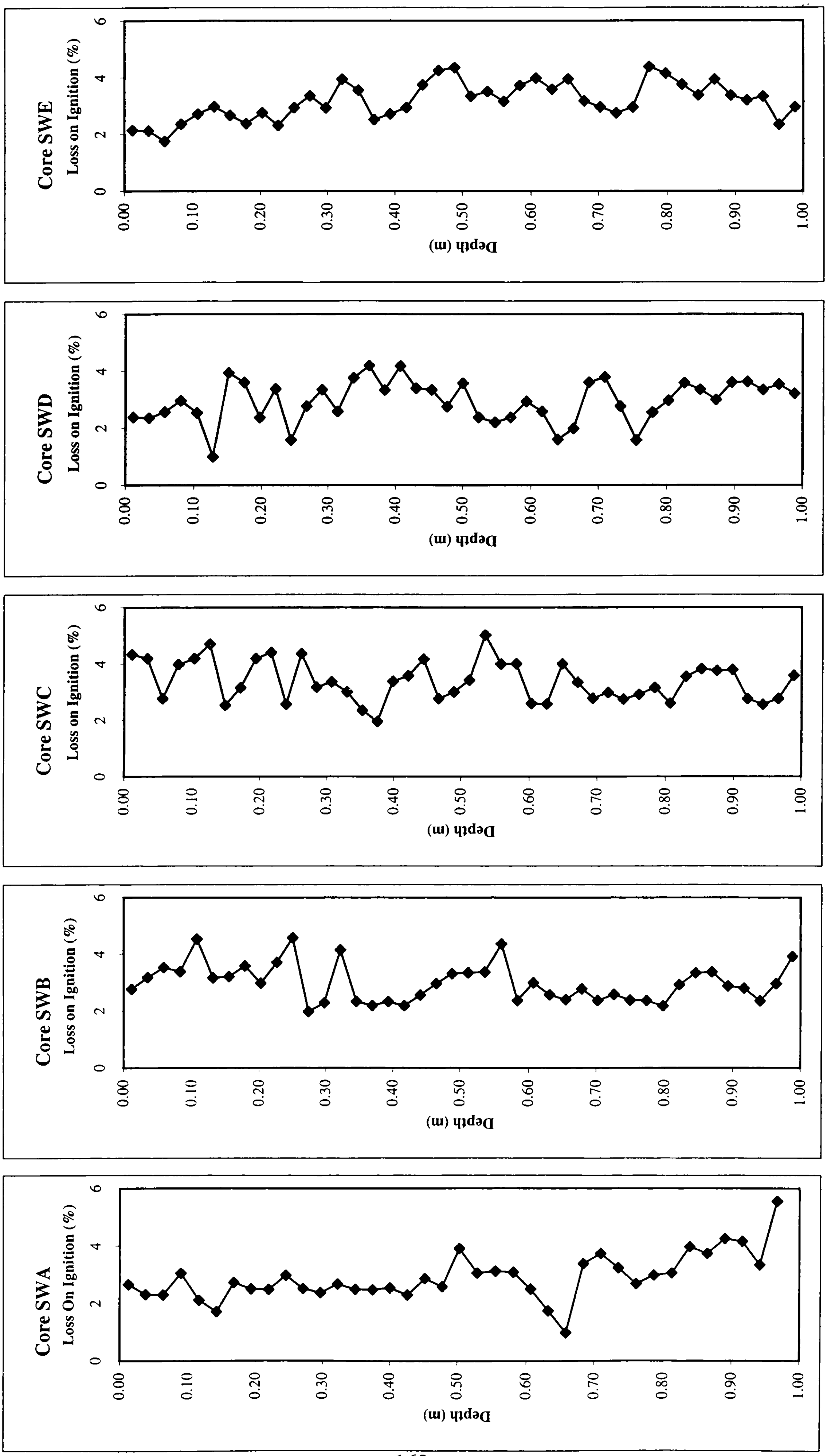


Figure 5.2 Percentage Loss on Ignition - Cores SWA, SWB, SWC, SWD, SWE

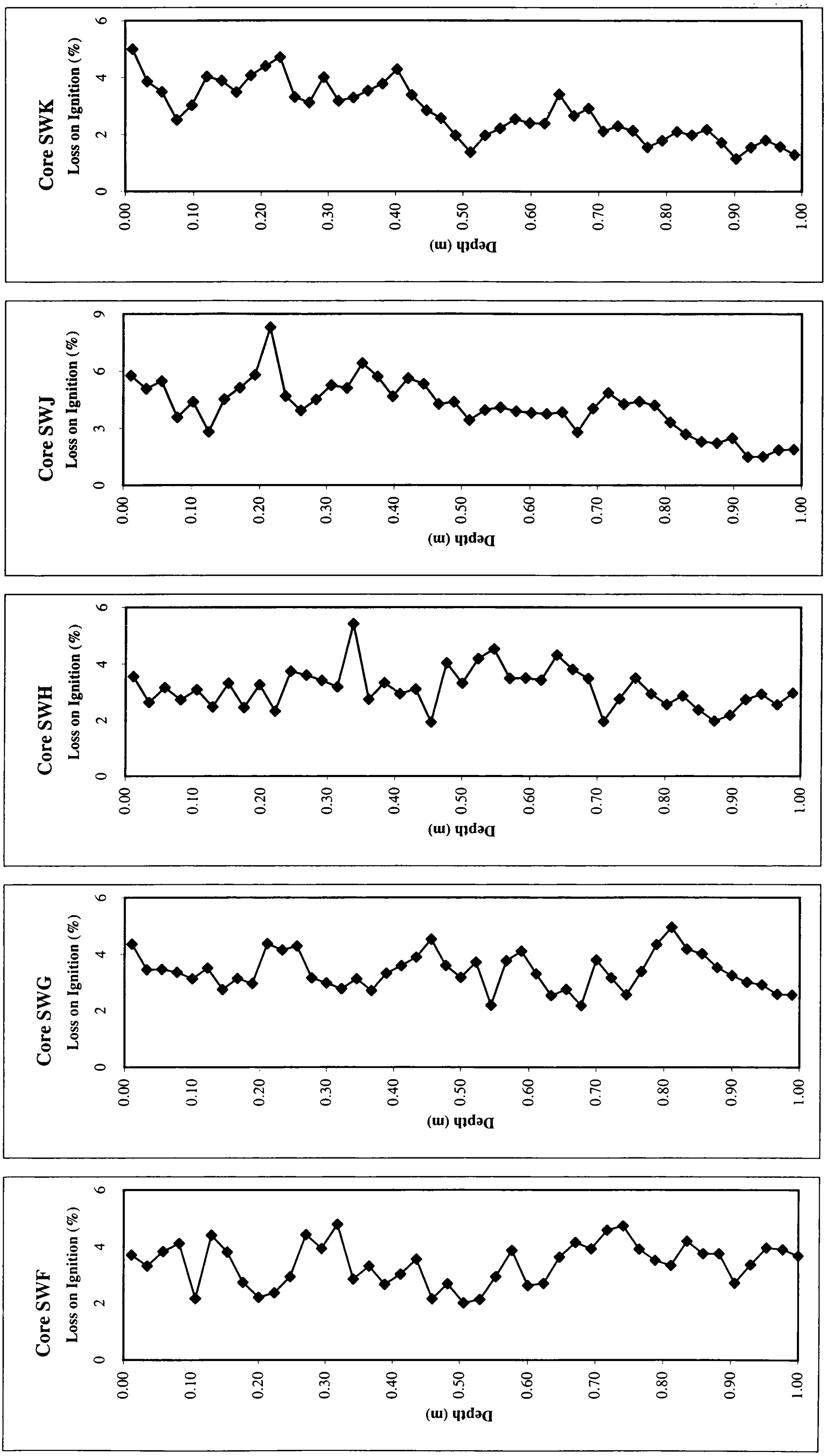


Figure 5.2 (cont.) Percentage Loss on Ignition - Cores SWF, SWG, SWH, SWJ, SWK

Core	% LOI	
	Range	Mean and standard deviation
SWA	1.0 - 5.0	2.9 +/- 0.8
SWB	2.2 - 4.6	2.98 +/- 0.67
SWC	2.0 - 5.0	3.38 +/- 0.71
SWD	1.0 - 4.2	2.94 +/- 0.73
SWE	1.7 - 4.4	3.17 +/- 0.65
SWF	2.0 - 4.7	2.0 +/- 4.7
SWG	2.2 - 5.0	3.39 +/- 0.65
SWH	1.9 - 5.4	3.14 +/- 0.71
SWJ	1.5 - 8.3	4.14 +/- 1.38
SWK	1.1 - 5.0	2.8 +/- 0.98

Table 5.3 % LOI summary statistics for Southwick cores

The % LOI for core SWA, located on the mudflat, does not exhibit a great deal of variability, especially between 17 cm depth and 43 cm, although there are small peaks at 9 cm, 25 cm, 50 cm There is a general increase in the % LOI towards the bottom half of the core except for a distinct trough in values between 61 cm and 68 cm.

Core SWB is also located on the mudflat, 8 m from the marsh edge towards Southwick Water. While there is little variation in values down the length of the core there are peak values at depths of 11 cm, 25 cm, 32 cm and 56 cm.

Core SWC is situated on the middle marsh, 2 m from the edge of a small creek. The core has a number of peaks and troughs in the % LOI profile down to 70 cm. Below this the % LOI increases a small amount for 20 cm and then reduces again. There are peak values at depths of 13 cm, 22 cm, 26 cm, 44 cm, 53 cm and 65 cm.

Core SWD is located on the bank of the main creek where the primary marsh grades to middle. The core profile is extremely variable with no distinct trend.

Core SWE is situated on the inner bend of a meander on the largest creek in the study area. The general trend in the profile seems to be an increase in % LOI to a depth of 80 cm. The general trend is then reversed with the % LOI reducing towards the base of the core. As with the other cores discussed so far, there are a number of peaks and troughs down the profile which mask the general trend.

Core SWF is located 2 m from the bank of the main creek, within the middle marsh and There is no distinctive trend down the profile, although there are a number of peaks and troughs. The most prominent peaks are at 13 cm, 27 cm, 32 cm and 74 cm and the most prominent troughs are at 11 cm and 20 cm.

Core SWG is located 20 m upstream from SWF, also 2 m from the creek bank. The top 40 cm of the core has a very uniform % LOI except for a peak between 21 cm and 26 cm. The core profile between 40 cm and 81 cm has a number of peaks and troughs. Below 81 cm, the % LOI reduces steadily until the base of the core.

Core SWH is on the middle marsh next to one of the smaller creeks. The general trend down the core profile is a fairly constant % LOI but again there are a number of peaks and troughs which mask this trend. There are distinctive peaks at 34 cm and troughs at 45 cm and 71 cm.

Core SWJ is in the middle marsh away from any creeks or pans. The value of 8.3 % at a depth of 22 cm is by far the highest value in any of the cores analysed. It was noted before the core was dried and segmented that this part of the core was very dark in colour with a sticky, fine-grained texture, a feature not seen in other Southwick cores. With the exception of this peak, the general trend in the profile is a reduction in the % LOI down the core.

Core SWK is in the upper marsh 2 m from a pan system. The large standard deviation, compared to the other cores, reflects a distinct decrease in the % LOI from the top of the core to the bottom. The general trend is overridden by a number of peaks and troughs similar to the other cores mentioned.

On the whole it can be said that there is a great amount of variability in the organic content of the cores throughout the whole marsh. The only discernible trends are in Core SWA on the mudflat which shows an increase with depth and in Cores SWJ and SWK, which lie near or on the high marsh and which show a reduction in % LOI with depth.

The main pattern which can be identified is that there are a number of peaks and troughs in the % LOI data which suggests a sedimentation regime in which organic rich sediment is deposited between phases of organic poor sediment deposition.

5.1.6 Radionuclide specific activity profiles

Each of the cores described in Table 5.2 and Section 5.1.5, was analysed for ^{137}Cs and ^{241}Am to determine the spatial distribution of radionuclides across the marsh. The results are given in Appendix 1, Table (iii) as specific activities in Bequerels per kilogram (Bq kg^{-1}). The $^{137}Cs/^{241}Am$ activity ratios for all samples are also recorded in Table (iii).

There is a large variation in the specific activities of both ^{137}Cs and ^{241}Am highlighting the heterogeneous nature of radionuclide deposition in the saltmarsh. In general the ^{137}Cs values are greater than corresponding values for ^{241}Am but both nuclides show similar distribution trends. The range of values for ^{137}Cs across the study area is from 46 Bq kg^{-1} to 1870 Bq kg^{-1}. For ^{241}Am, the range is from 4 Bq kg^{-1} to 1154 Bq kg^{-1}. Specific activity profiles for the cores are shown in Figure 5.3.

Core SWA is a relatively featureless profile with a slight increase in ^{137}Cs and ^{241}Am concentrations towards the base of the core. The range for ^{137}Cs is from 46 Bq kg^{-1} to 288 Bq kg^{-1} and the range for ^{241}Am is 39 Bq kg^{-1} to 207 Bq kg^{-1}. The $^{137}Cs/^{241}Am$ activity ratios range from 1.1 to 2.8. The value of 2.8 at 9 cm is a slight anomaly as the majority of samples have a ratio less than 1.6. There is a slight increase in the ratio towards the base of the core.

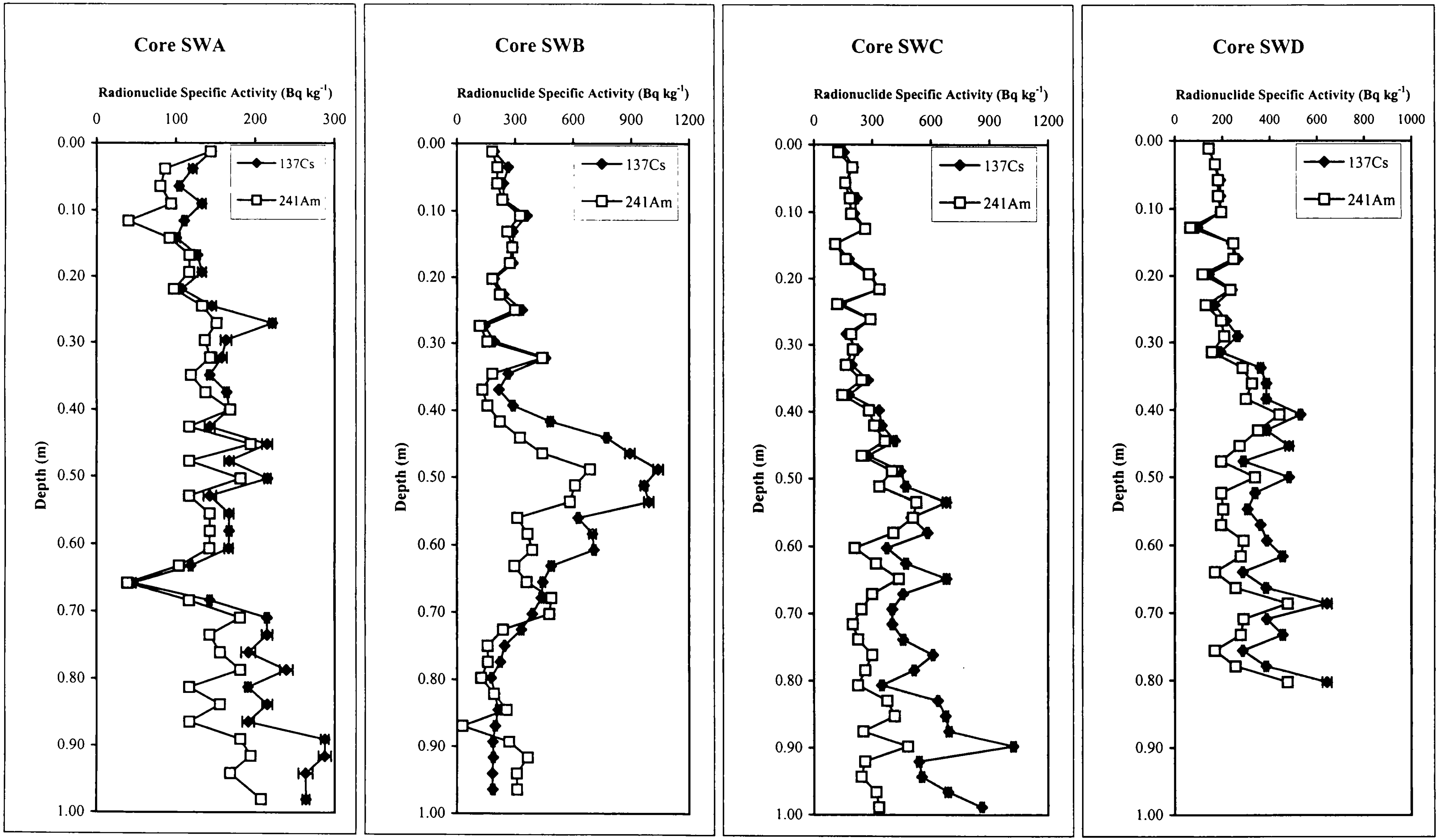


Figure 5.3 Radionuclide specific activity profiles - Cores SWA, SWB, SWC, SWD

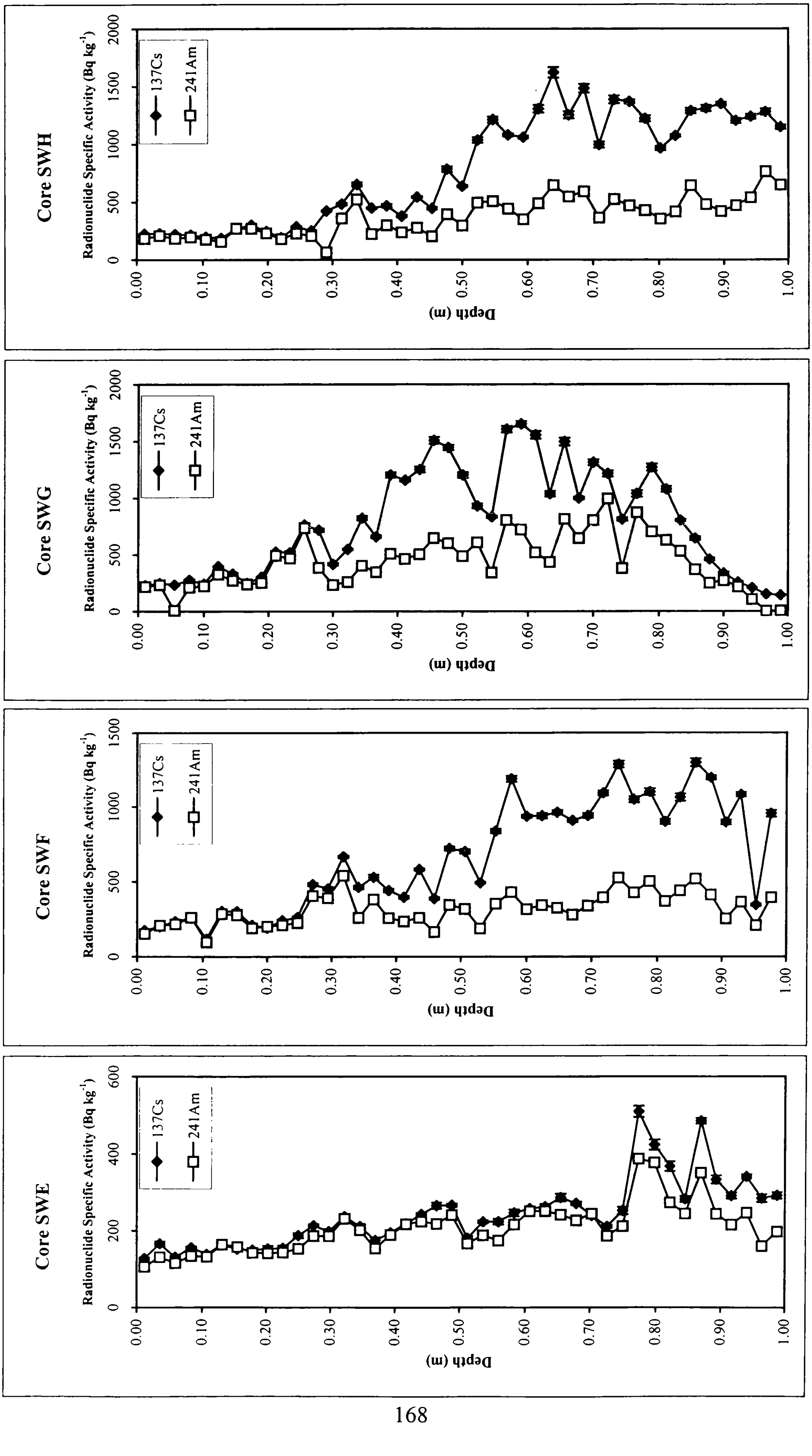
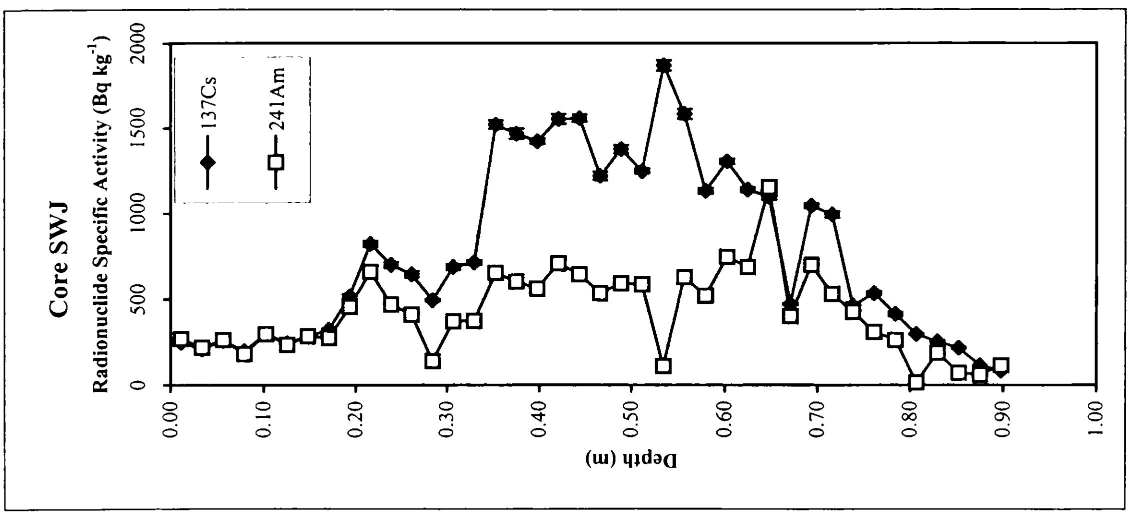


Figure 5.3 (cont.) Radionuclide specific activity profiles - Cores SWE, SWF, SWG, SWH



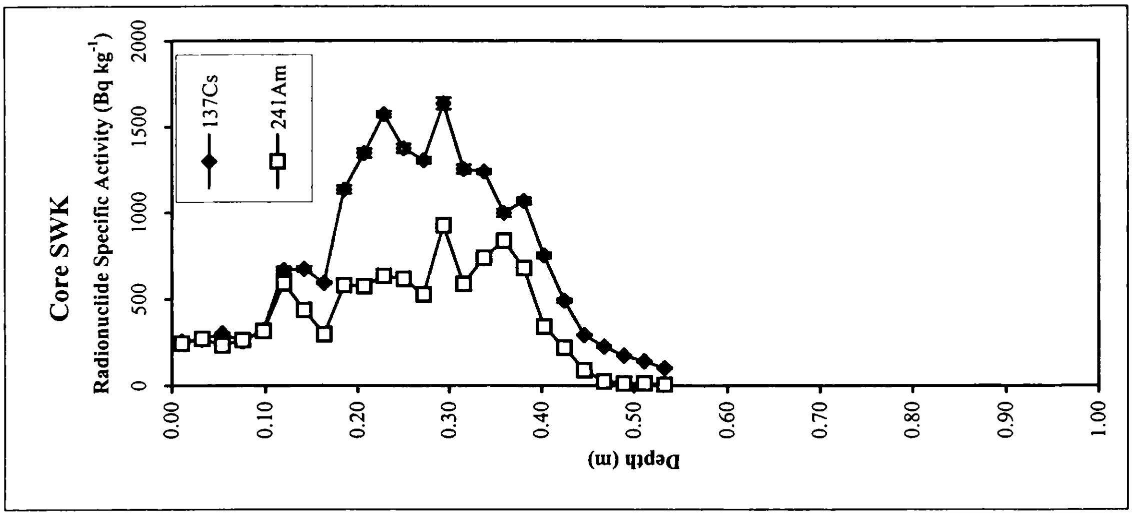


Figure 5.3 (cont.) Radionuclide specific activity profiles - Cores SWJ and SWK

The vertical distribution patterns for ^{137}Cs and ^{241}Am in Core SWB are markedly different from those of SWA. There are a number of peaks and troughs in the profile of specific activities of both ^{137}Cs and ^{241}Am, with a major peak at 50 cm and smaller peaks at 33 cm and 60 cm. The range in ^{137}Cs specific activities is from 143 Bq kg^{-1} to 1038 Bq kg^{-1}. The range in ^{241}Am values is from 26 Bq kg^{-1} to 686 Bq kg^{-1}. The ^{137}Cs and ^{241}Am values are very similar to a depth of 30 cm and, as such, the $^{137}Cs/^{241}Am$ activity ratio to this point ranges from 1.0 to 1.3. From 35 cm until the base of the core, the specific activities of the two radionuclides and the $^{137}Cs/^{241}Am$ activity ratio, become much more variable. Coincident with the major peak in specific activities, the ratio increases to a maximum of 2.4 at 44 cm depth. As the specific activities reduce towards the base of the core, there is a similar reduction the ratio to a minimum of 0.6. This is one of the few locations where the ^{241}Am concentration is greater than ^{137}Cs.

Core SWC does not exhibit peak specific activities in the same manner as SWB but still differs from the profile shown in core SWA. There is a distinct increase in the specific activity of both radionuclides towards the base of the core. The range in the ^{137}Cs values is from 111 Bq kg^{-1} to 1022 Bq kg^{-1} and the range for ^{241}Am is from 109 Bq kg^{-1} to 525 Bq kg^{-1}. Superimposed upon an increase with depth, are a number of peaks and troughs in the specific activities down the core. In general, the peaks and troughs in the ^{137}Cs and ^{241}Am data are coincident, with the ^{137}Cs peaks being more extreme. The $^{137}Cs/^{241}Am$ activity ratio increases towards the base of the core and ranges from 0.9 to 2.6.

The profiles of radionuclide specific activities in Core SWD are very similar to those for SWC. There is a general increase in both specific activities and activity ratios towards the base of the core, with a number of peaks and troughs superimposed on the general trend. As with SWC the positions of the peaks and troughs in the ^{137}Cs and ^{241}Am activity are coincident. The range of values for ^{137}Cs is from 94 Bq kg^{-1} to 852 Bq kg^{-1}, whereas for ^{241}Am the range is from 65 Bq kg^{-1} to 487 Bq kg^{-1}. The activity ratio values range from 1.0 to 1.9.

Core SWE, like SWA, has a featureless profile. The location of SWE on the inner bend of a meander resembles the mudflat location (SWA) because the area is subject to frequent flooding, sedimentation occurs rapidly and the little pioneer vegetation that occurs is recent. There is a slight increase in the ^{137}Cs and ^{241}Am concentrations towards the base of the core below 75cm depth and there is greater variability in this section. The ^{137}Cs range is from 131 Bq kg^{-1} to 510 Bq kg^{-1}. The ^{241}Am range is from 106 Bq kg^{-1} to 387 Bq kg^{-1}. The activity ratio is remarkably constant from the surface to 75 cm depth with a range 1.0 to 1.3. Below 75 cm the activity ratio is generally higher, ranging from 1.1 to 1.8.

Core SWF marks a change in the character of the specific activity profiles. To a depth of 32 cm, the ^{137}Cs and ^{241}Am values are very similar and the corresponding activity ratios range from 0.9 to 1.2. Below 32 cm the ^{137}Cs and ^{241}Am specific activities begin to diverge with the ^{137}Cs values being much greater than those of ^{241}Am. There are coincident peaks and troughs in the two profiles but the ^{137}Cs peaks are much greater. Below 53 cm the ^{137}Cs specific activities are significantly greater than the ^{241}Am values, with $^{137}Cs/^{241}Am$ ratios between 1.7 and 3.0. The ^{241}Am profile exhibits generally small variations although there is a slight increase in activity towards the base of the core. The ^{241}Am specific activity range is from 97 Bq kg^{-1} to 541 Bq kg^{-1}. In contrast, the ^{137}Cs specific activities increase significantly down the core, with a range between 118 Bq kg^{-1} and 1298 Bq kg^{-1}.

Core SWG exhibits distinct sub-surface maxima in both the ^{137}Cs and ^{241}Am profiles. The range of ^{137}Cs values is from 143 Bq kg^{-1} to 1655 Bq kg^{-1}, while the ^{241}Am range is from 4 Bq kg^{-1} to 997 Bq kg^{-1}. Defining where the main peak in values begins and ends is difficult because of the number of peaks and troughs which overprint the main trend. The peak extends approximately from 37 cm to 81 cm in both ^{137}Cs and ^{241}Am profiles. The turning point of the main peak is at 59 cm for ^{137}Cs and at 72 cm for ^{241}Am. While the sub surface maxima of the two radionuclides do not coincide, the positions of the other peaks and troughs evident in the profile do.

Core SWH resembles Core SWF in that there is a distinct increase in both the ^{137}Cs and ^{241}Am specific activities with depth and the sub-surface maxima are not as clearly defined as in core SWG. The specific activities of the two radionuclides in the top 35 cm of the core are very similar and the $^{137}Cs/^{241}Am$ ratio ranges from 1.0 to 1.3, with a value of 6.6 at 29 cm. Below 35 cm the ^{137}Cs and ^{241}Am specific activities diverge. The profile for ^{241}Am increases steadily but not extensively towards the base of the core, with a range from 158 Bq kg^{-1} to 762 Bq kg^{-1}. The ^{137}Cs profile is more dramatic with a range of 191 Bq kg^{-1} to 1621 Bq kg^{-1}. The activity ratios below 35 cm range from 1.6 to 3.0, with the highest ratios coincident with the highest activities.

Core SWJ has a similar profile to Core SWG, with the difference that the extent of the subsurface maximum is more restricted. The high ^{137}Cs and ^{241}Am values begin at 35 cm and finish at 72 cm. As with SWG, there are a number of subsidiary peaks and troughs over the main trend, with the most distinct at 22 cm. The activity ratios again reflect the disparity between the ^{137}Cs and ^{241}Am peak concentrations. The ratio within the top 30 cm ranges from 0.9 to 1.6 with the peak in the ratios occurring at a lower depth than the peak radionuclide activities. The ratio then reduces again to a range between 0.7 and 1.9 towards the base of the core.

Core SWK has the most clearly defined sub-surface maxima in specific activities for this study area. Analysis of the core ceased at a depth of 53 cm because the ^{241}Am specific activities reached the detection limits. The peak activities extend from a depth of 18 cm to 40 cm. The ^{137}Cs activities are again much greater than those of ^{241}Am. The $^{137}Cs/^{241}Am$ activity ratios in the top 10 cm of the core are between 1.0 and 1.5. The activity ratios in the locations of the peak concentrations are higher ranging from 2.0 to 2.5. The activity ratios deeper than the peak concentrations are variable and significantly higher values occur, but the errors are relatively large as a result of the error in the ^{241}Am analysis.

To summarise the main trends: the cores collected from the mudflat areas and from the pioneer marsh (Cores SWA, SWB, SWC, SWD, SWE) all show increases in specific activities of both ^{137}Cs and ^{241}Am with depth but there are no discernible peaks in the profiles. The exception to this is core SWB which does have a small peak at a depth of 50 cm. Cores in the middle marsh and high marsh show distinct peaks in the radionuclide profile. Cores located inland, for example SWK, have peak radionuclide activities at a shallower depth than cores from positions nearer Southwick Water. The depth over which the high activities are present also decreases in cores further inland. For example, in core SWK the high ^{137}Cs activities extend from 18 cm to 38 cm, a depth of 20 cm, whereas in core SWJ the high ^{137}Cs concentrations extend from 35 cm to 69 cm, a depth of 34 cm.

5.1.7 Analysis of sediment sizes within cores

A number of samples from each core were sieved and analysed using the Coulter 230LS laser particle sizer. The results from the sieving, expressed as the differential percentage (as opposed to cumulative percentage) coarser than the sieve size, are given in Appendix 1, Table (iv). The results from the analysis using the Coulter 230LS are expressed as the percentage of the sample finer than a particular size and are given in Appendix 1, Table (v).

The sediment trapped by the 125 μm sieve was examined under a magnifying glass and appeared to be largely agglomerates of smaller particles, rather than individual particles. The method of dis-aggregation used prior to sieving (using a mortar and pestle) was necessarily gentle to avoid breaking and grinding any particles, resulting in some clumping of the sediment. The size fraction below 125 μm, therefore is important to consider although, as a consequence of the relationship between fine sediment (silts and clays) and radionuclide concentrations (for example, Aston and Stanners, 1981, Clifton and Hamilton, 1982, Pentreath *et al,* 1984), the most detailed investigation is of the less than 63 μm fraction.

Analysis of sieving results from all the cores illustrates that 89.4% of sediment is less than 125 μm (with a standard deviation of 3.2%) and that 53.1% is less than 63 μm (standard deviation 4.3%). This clearly shows that the sediment on Southwick marsh as a whole, can be considered to be fine in character. Table 5.4 illustrates this in more detail.

Core	SWA	SWB	SWC	SWD	SWE	SWF	SWG	SWH	SWJ	SWK
Mean % less than 125μm	86.08	93.04	93.03	90.88	93.6	89.95	86.1	89.3	84.9	87.7
Standard deviation	11.9	2.6	2.4	5.6	1.5	1.9	3.6	2.9	9.8	4.2
Mean % less than 63μm	47.1	56.0	52.3	47.6	55.9	58.7	54.5	59.3	51.3	50.2
Standard deviation	8.5	9.1	7.5	2.0	12.7	8.4	8.1	8.5	9.7	4.5

Table 5.4 Fine fraction characteristics for Southwick cores

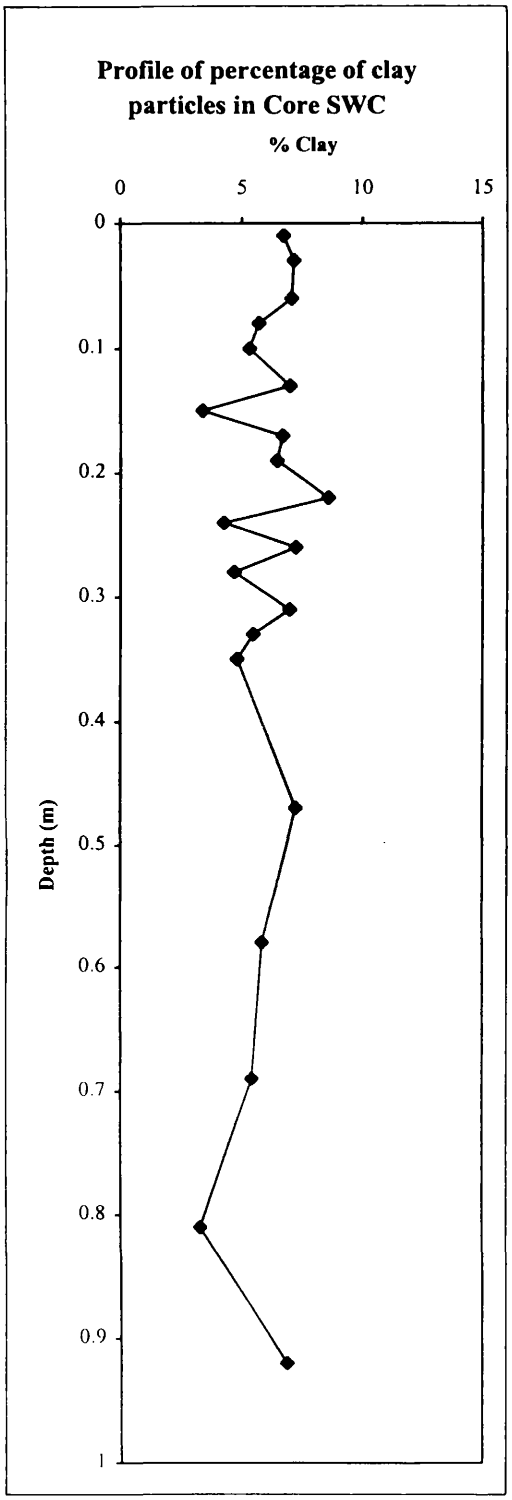
Further analysis of the fine fraction was completed using the Coulter LS 230. A summary of the mean results from each core is given in Table 5.5. From this table, differences in the sediment size across the marsh can be discerned. All cores have more than 60% of the sediment less than 63 μm. Cores SWC, and SWF-SWK have more than 70% of the sediment less than 63 μm. These cores also have higher percentages of clay* (less than 3.9 μm), indicating an overall finer texture than cores SWA, SWB, SWD and SWE.

Within individual cores there does not appear to be any clear pattern or trend with regard to sediment size down the length of the core. This is illustrated in Figure 5.4.

* Definition of clay by Udden (1914) and Wentworth (1922) as referenced in Gale and Hoare (1991).

Core	SWA	SWB	SWC	SWD	SWE	SWF	SWG	SWH	SWJ	SWK
Mean % less than 63μm	65.1	67.1	71.7	67.2	68.5	72.5	78.5	73.8	77.4	77.6
Standard deviation	5.3	6.2	5.1	3.1	4.2	2.6	4.5	4.7	4.9	4.0
Mean % less than 32μm	17.1	20.5	24.9	18.8	21.1	26.3	33.7	29.0	34.3	32.5
Standard deviation	5.2	5.2	6.1	1.7	4.7	4.2	6.7	5.8	6.4	5.8
Mean % less than 16μm	10.5	12.9	15.3	11.0	12.7	15.8	20.5	17.8	21.1	20.0
Standard deviation	3.3	3.5	1.1	0.9	2.8	2.7	3.9	3.7	4.0	3.8
Mean % less than 7.8μm	7.55	8.4	9.9	7.1	8.7	10.2	12.9	10.9	12.9	12.7
Standard deviation	2.2	2.3	2.3	1.5	1.5	1.6	2.5	2.3	2.2	2.4
Mean % less than 3.9μm	5.3	5.4	6.0	4.8	6.0	6.2	7.5	6.0	7.3	7.6
Standard deviation	1.5	1.6	1.3	1.5	0.8	1.5	2.0	1.6	1.7	1.5

Table 5.5 Analysis of fine fraction of Southwick cores



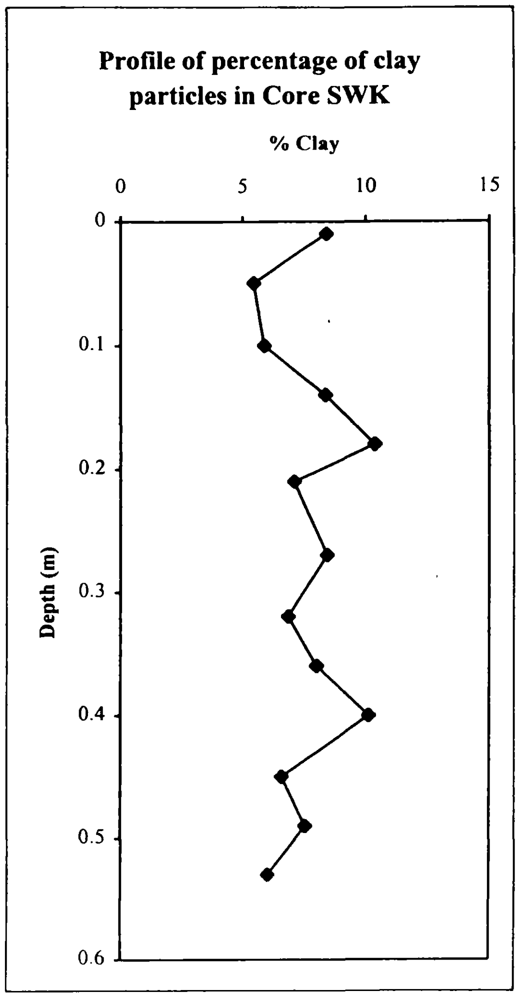


Figure 5.4 Percentage of clay in Cores SWC and SWK

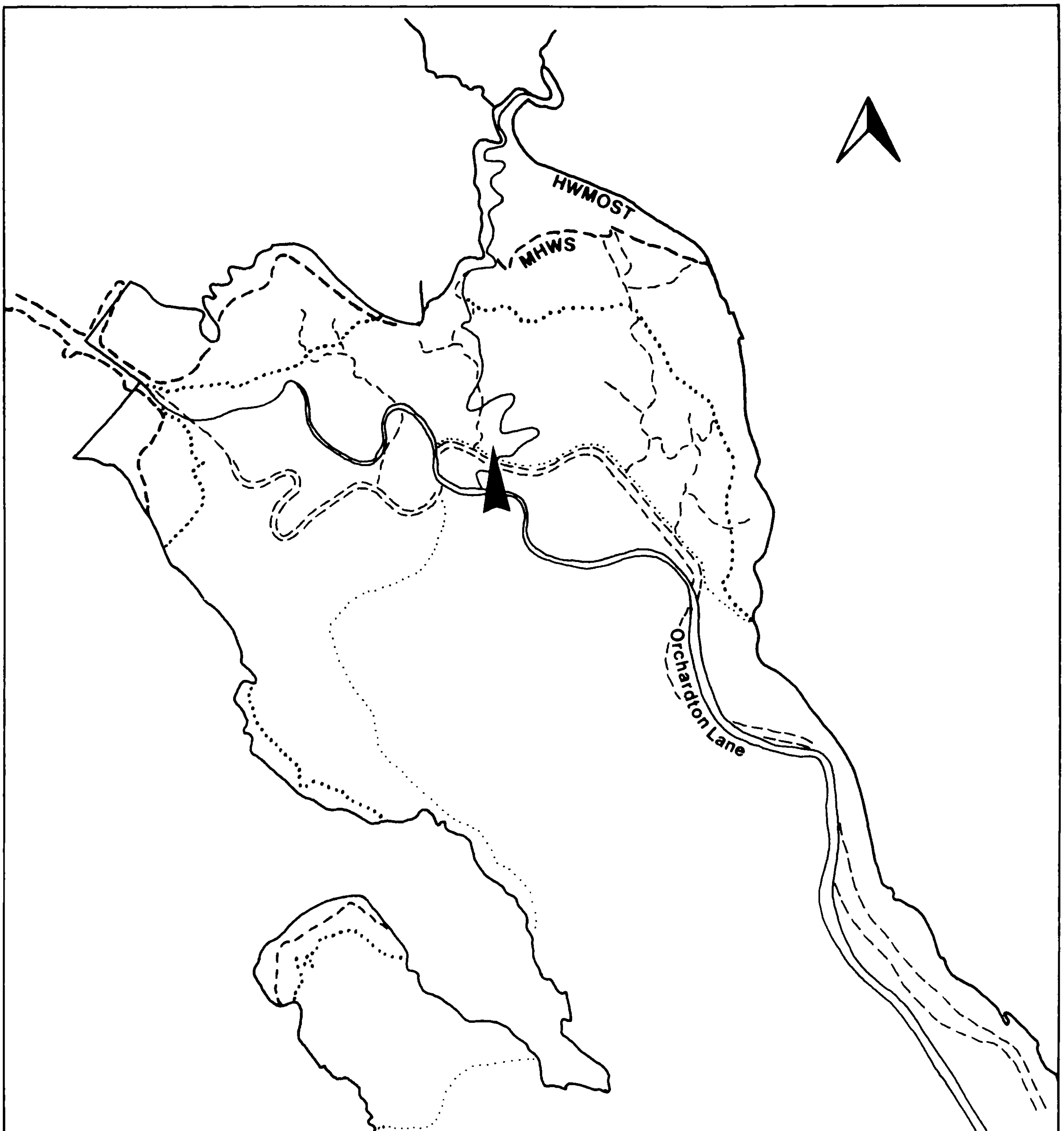
5.2 Orchardton

5.2.1 Setting and Historical Development

Orchardton marsh is located around grid point NX85 81 53, at the head of Orchardton Bay. This is one of several bays cut into granitic bedrock imparting a very broken coastline to this part of the Solway Firth. The bay is protected as a biological Site of Special Scientific Interest and also lies within the Stewartry Environmentally Sensitive Area and National Scenic Area (Buck, 1993). It can be classified as a Northern European, macro-tidal, estuarine marsh, with natural *Puccinellia* vegetation, planted with *Spartina.*

Development of the marsh, investigated using two successive maps from 1854 and 1982, (Figure 5.5) is difficult to determine because of a lack of information on the early maps. The 1854 map describes the area at the head of the bay as "inking" which according to Bridson (1979) (investigating marshes on Caerlaverock) is a word not referred to in the Scottish Dictionary nor used on subsequent maps. Bridson presumes that the word refers to accreting merse, however, given the small amount of marsh shown on the 1950, 1: 25 000 scale map of Orchardton, it is more likely that the description of inking is mudflat, rather than saltmarsh. The northern and eastern sides of the bay were reclaimed some time after 1854, although it is not clear when this occurred. The reclaimed areas are now used for cattle and sheep grazing. The extent of marsh has increased rapidly over the last 40 years facilitated in 1951 by the planting of *Spartina* (Pye and French, 1993).

The *Spartina* planting has changed the character of the marsh in Orchardton Bay. The marsh at the head of the bay displays the remnants of original marsh, with the vegetation comprising pioneer species *Salicornia* and *Puccinellia* and secondary species such as *Limonium* and *Halimione.* There are also a number of grassland species with *Festuca* dominating. As a consequence of the fronting *Spartina* marsh, this area of marsh is now infrequently inundated and is deprived of tidal waters and sediment. The area now represents a transition from wetland vegetation rather than the development of true high saltmarsh vegetation (Harvey and Allan, 1998).



1854 MAP LEGEND		1982 MAP LEGEND	
HWMOST	High Water Mark of Ordinary Spring Tide	MHWS	Mean High Water Spring
	Tidal Channel		Tidal Channel
	Edge of 'inking'		Edge of Saltmarsh

Figure 5.5 Compilation of 1:10 000 maps from 1854 and 1982 demonstrating extent of change on Orchardton Merse (arrow indicates study area)

A distinct boundary occurs between the grassland and the *Spartina* marsh which is unlike other marshes, where zoning of vegetation in the marsh occurs gradually.

Prior to the planting of *Spartina* at Orchardton, the primary coloniser was *Salicornia,* with *Puccinellia* establishing later (Morss, 1925-26). After the initial *Spartina* planting, *Salicornia* was no longer able to compete because of the adaptable nature of *Spartina* (Ranwell, 1972). This situation, however, is changing and once more, *Salicornia* is abundant in areas proximal to Orchardton Lane, the main tidal channel in the bay.

The position of the study site at Orchardton is shown by an arrow in Figure 5.5.

5.2.2 Geomorphology, vegetation and recent changes in the study site

The study area within Orchardton concentrates on the *Spartina* marsh and the geomorphology of the area is shown in Map 2a (located in the map folder). The vegetation and changes in the marsh over the study period are given in Map 2b. The study site occupies an area of 6335 m^2. This marsh is very different from the Southwick site, the surface is muddier and there are few continuous areas of vegetation. The marsh has a number of meandering creeks and parts of two of these are included in the study area. There are two distinctive marsh areas: the primary *Salicornia* marsh and the *Spartina* marsh.

5.2.2.1 Salicornia *marsh*

The *Salicornia* marsh occupies a small area near to the major tidal creek, Orchardton Lane, where the height of the marsh is approximately 1 m higher than the surrounding unvegetated mudflat. The area occupied by *Salicornia* is drier and better drained, than any other part of the marsh. The success of the *Salicornia* colonisation has varied over the study period and in 1995, the *Salicornia* stand was quite dense with around 50% coverage in topographically higher areas. In 1996 this had dropped to 30% but increased again slightly in 1997. In 1997 the lateral extent of *Salicornia* had increased by a maximum of 2 m.

The reduction in *Salicornia* in 1996 can perhaps be attributed to an increase in the extent of an algal mat covering this area thereby curtailing the development of the *Salicornia.* This algae was not evident in 1995 or 1997. A possible explanation for this is that in 1996 the summer was very wet and quite stormy. More frequent inundation of the marsh as a result of higher water levels would have resulted in the development of algal mats rather than pioneer saltmarsh vegetation because the mats can withstand greater periods of inundation.

Inundation of this higher part of the marsh comes directly from Orchardton Lane and occurs at all times other than low neap tides. A few poorly defined saltpans, devoid of vegetation, occur.

5.2.2.2 Spartina *marsh*

The *Spartina* marsh is separated from the *Salicornia* marsh by approximately 20 m of mudflat. Within the mudflat there are a few small creeks which have elongated over the study period, although some of the smallest creeks are ephemeral, changing direction and, at times, completely infilling with sediment. At the landward edge of the mudflat there are isolated patches of *Spartina* but these have not extended their limit over the study period.

Separating the mudflat from the main *Spartina* marsh is a small cliff, 30 cm at it highest point. The marsh surface, at first sight, appears rather homogeneous because there is little difference in the vegetation composition across the study area. Detailed inspection however reveals subtle changes in the density of the Spartina stands as a consequence of the hummocky marsh surface. Higher areas of the marsh are slightly drier (although the marsh as a whole is very muddy) and the *Spartina* is denser. The height of the hummocks is only a few centimetres, but this is sufficient to be reflected in the vegetation. On the highest areas (perhaps only 10 cm height difference) there are other pioneer species evident such as *Puccinellia* and *Salicornia.*

The highest areas of the marsh are adjacent to the creeks, predominantly in areas towards the north of the site and are distinctive because they lack *Spartina*. These areas are dominated by *Puccinellia* with occasional *Salicornia, Aster maritima, Plantago* and

Triglochin. The meandering nature of the creeks means that there is little differentiation in the inundation of the marsh within the study area. The higher hummocky areas and the levees around the creeks will, however, be inundated for a shorter period. Areas of the marsh at a distance from creeks also have a reduced hydroperiod.

The creeks in this area rarely exceed 3 m in width (although they are wider in other parts of the marsh) and are approximately 70 cm deep. Some have lengthened their reach by a small amount (10s of centimetres) over the study period via headward erosion of small tributary creeks. The tributary creeks are supplied with water draining from the marsh by rills, the inception of which occurs in the lower areas of marsh. The very muddy nature of the marsh indicates that it drains very slowly and the process is never complete before the next inundation event. No saltpans occur in this part of the marsh.

Overall there has been little change in the marsh over the study period with the exception of a small extension of the *Salicornia* marsh, erosion of the creek heads and modest changes in the composition of vegetation (introduction of *Puccinellia* and *Aster*) on the higher marsh areas.

5.2.3 Sedimentation in the study area

The location of the metal plates used to establish the sedimentation rates and patterns across the Orchardton marsh is given Map 2a and the calculated sedimentation rates (mm y^{-1}) are given in Appendix 2, Table (i) with a summary in Table 5.6. The results range from a minimum of -1.6 cm y^{-1} to 8.1 cm y^{-1}. As with Southwick, a few of the plates were not relocated and in this instance were probably eroded away by the tide soon after insertion.

The highest sedimentation rates recorded were from plates located on the mudflat between the *Salicornia* marsh and the *Spartina* marsh. Plate 1, located on the southern edge of the *Salicornia* marsh had a rate of 4.9 cm. The other mudflat plates, to the north of the *Salicornia* marsh, all indicated rates slightly higher than this: Plates, 4, 7, 8, and 13 have rates of 7.6 cm y^{-1}, 6.2 cm y^{-1}, 8.1 cm y^{-1} and 5.6 cm y^{-1} respectively.

Plates 3 and 5 on the pioneer *Salicornia* marsh recorded net erosion rates of –1.6 cm y^{-1} and -1.3 cm y^{-1} respectively, while Plate 6 indicated a sedimentation rate of 1.1 cm y^{-1}. The pioneer areas of *Spartina* marsh, Plates 9 and 12 have accretion rates of 4.1 cm y^{-1} and 2.5 cm y^{-1} which is lower than the rates found on the mudflat.

Plate	Position on marsh	Accretion rate (cm y^{-1})
1	Mudflat	4.9
2	Mudflat	*
3	Pioneer marsh - *Salicornia*	-1.6
4	Mudflat	7.6
5	Pioneer marsh - *Salicornia*	-1.3
6	Pioneer marsh - *Salicornia*	1.1
7	Mudflat - nr. small channel	6.2
8	Mudflat - nr. small rill	8.1
9	Pioneer marsh - *Spartina*	4.1
10	Mudflat	*
11	*Spartina* marsh - cliff edge	0
12	Pioneer marsh - *Spartina*	2.5
13	Mudflat	5.6
14a	*Spartina* marsh - hummock	0.8
14b	*Spartina* marsh - hummock	0.7
15	*Spartina* marsh	0.3
16	*Spartina* marsh - hummock	0.9
17	*Spartina* marsh	-0.7
18	*Spartina* marsh - hummock	-0.3
19	*Spartina* marsh - hummock	-0.2
20	*Spartina* marsh - nr. creek	-0.3
21	*Spartina* marsh - nr. creek	-0.7
22	*Spartina* marsh - hummock	0.2
23	*Spartina* marsh	0.5
24	High marsh	0.4
25	*Spartina* marsh - nr. creek	0.1
26	*Spartina* marsh	0.4
27	High marsh - nr. small channel	0.5
28	High marsh - nr. creek	0.1
29	High marsh - nr. creek	*
30	*Spartina* marsh	0.4
31	High marsh	0.6
* unable to calculate (see text)		

Table 5.6 Summary of Orchardton plate results

This is not what would be expected, because vegetation is generally considered to promote increased sedimentation.

The sedimentation rates on the *Spartina* marsh measured range from -0.7 cm y^{-1} to 0.9 cm y^{-1}. Not only are these values very small compared to rates observed at Southwick, but there is little variation across the extent of the marsh.

Plates 14a and 14b are only one metre apart on a drier hummock and indicated accumulation rates of 0.8 cm y^{-1} and 0.7 cm y^{-1}, while Plate 16, also situated on a hummock, gave a rate of 0.9 cm y^{-1}. These are the highest rates measured on the *Spartina* marsh. Plates 18 and 19 are also positioned on hummocks but indicated rates of -0.3 cm y^{-1} and -0.2 cm y^{-1}.

The sedimentation rates towards the north end of the site, further inland from Orchardton Lane, are all very low but positive. Plates 15, 23, 26 and 30 are on slightly lower parts of the marsh where the cover of *Spartina* is quite sparse and generated similar rates: 0.3 cm y^{-1}, 0.5 cm y^{-1}, 0.4 cm y^{-1} and 0.4 cm y^{-1} respectively. The rates on the slightly higher areas which have more extensive vegetation coverage are again similar, with Plates 24, 27 and 31 indicating rates of 0.4 cm y^{-1}, 0.5 cm y^{-1} and 0.6 cm y^{-1}. The variation measured between the high and low areas of *Spartina* is barely outwith the error limits of +/- 1mm.

It is apparent that the sedimentation rates experienced on Orchardton are very different to those at Southwick. The observed rates are all very low except for those derived from plates located on the mudflat. The pattern of decreasing sedimentation rates with increasing height recognised on Southwick is not apparent here. If anything, areas which are slightly higher have greater rates of sedimentation. Sedimentation around the creeks is low.

5.2.4 Profiles of the study area

As with Southwick, the survey results revealed no changes in the level of the marsh and were therefore not used in the analysis.

5.2.5 Determination of organic content of sediment within marsh sediments

In similar fashion to Southwick, cores were taken across Orchardton marsh, divided and analysed for organic content (percentage loss on ignition (% LOI)) in order to determine the contribution of organic material to sedimentation of the marsh. The core locations are given in Table 5.7 and shown in Map 2a.

Core	Location
ORA	Mudflat near to main tidal channel
ORB	*Salicornia* marsh
ORC	Mudflat near to small ephemeral creek
ORD	Mudflat (poorly drained)
ORE	Primary *Spartina* marsh
ORF	Low area in *Spartina* marsh
ORG	*Spartina* marsh, 2m from creek
ORH	Middle of *Spartina* marsh on raised hummock
ORJ	*Spartina* marsh with secondary vegetation, 3m from creek
ORK	*Spartina* marsh with secondary vegetation

Table 5.7 Core locations on Orchardton Marsh

The results of these analyses are in Appendix 2, Table (ii).Graphs of each core profile are presented in Figure 5.14. Summary statistics are given in Table 5.8.

The range of values across the whole site is from 1.3% to 9.3%.

Core	% LOI	
	Range	Mean and standard deviation
ORA	1.4 - 3.6	2.4 +/- 0.55
ORB	1.8 - 4.6	2.5 +/- 0.6
ORC	1.8 - 6.6	2.8 +/- 0.8
ORD	2.0 - 3.8	3.3 +/- 0.4
ORE	1.3 - 4.6	3.3 +/- 5.9
ORF	1.8 - 5.0	3.3 +/- 0.9
ORG	2.4 - 7.4	4.3 +/- 0.9
ORH	3.2 - 7.2	5.18 +/- 1.1
ORJ	2.2 - 9.3	4.6 +/- 1.6
ORK	4.0 - 6.3	5.1 +/- 0.7

Table 5.8 % LOI summary statistics for Orchardton cores

Core ORA is located on the mudflat bank of Orchardton Lane which is the main tidal channel in Orchardton Bay. There is no distinct trend down the profile, although there is a slight increase in % LOI at the base of the core.

Core ORB is located on the *Salicornia* marsh and has summary statistics similar to ORA but there are three distinct peaks in the ORB profile at 56 cm, 68 cm and 93 cm. With the exception of these peaks the profile shows very little variability in the % LOI.

Core ORC, located 5 m north of the *Salicornia* marsh on the mudflat, has a slightly higher mean % LOI than the previous cores. There is a major peak at 66 cm with minor peaks at 8 cm, 25 cm and 33 cm. The rest of the core shows no obvious trend.

Core ORD is located in the middle of a very muddy part of the mudflat which is the first to receive water from the incoming tide and the last area to drain. The low variability (as indicated in the low standard deviation reported in Table 5.8) is strikingly illustrated in the graph, especially to a depth of 50 cm. Below 50 cm the variability increases with small peak at 61 cm.

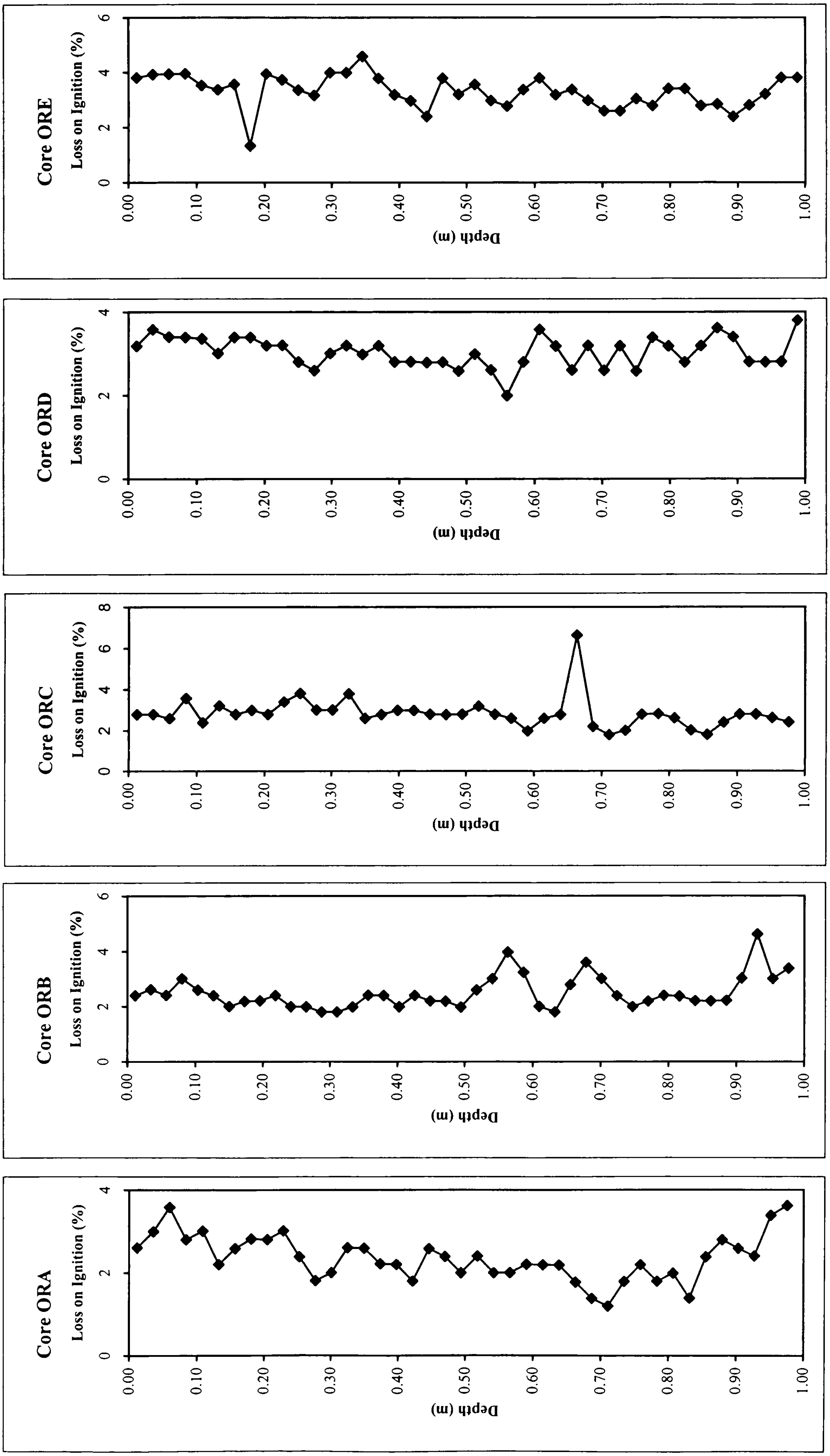


Figure 5.6 Percentage Loss on Ignition - Cores ORA, ORB, ORC, ORD, ORE

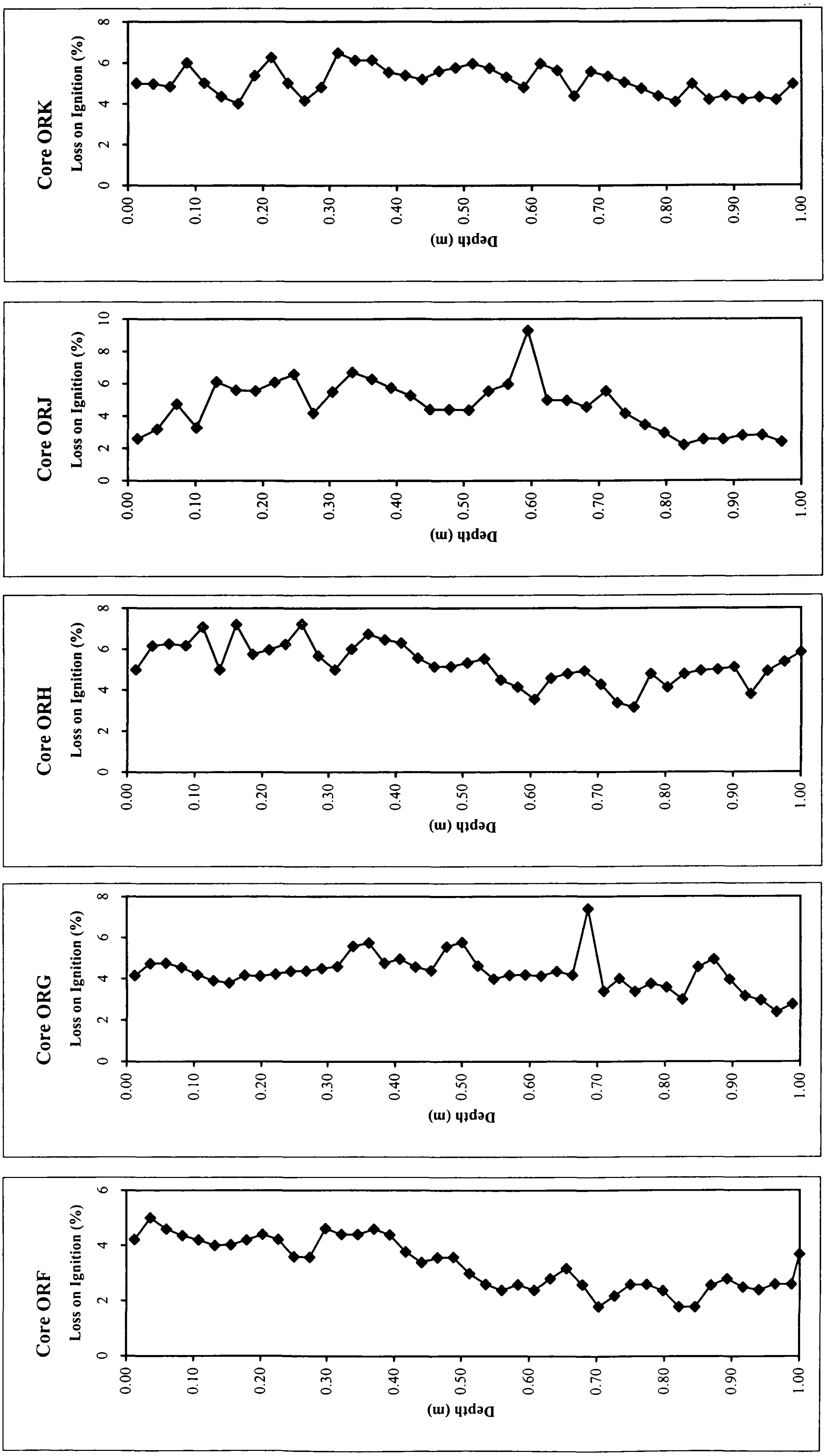


Figure 5.6 (cont.) Percentage Loss on Ignition - Cores ORF, ORG, ORH, ORJ, ORK

Core ORE is located on the mudflat 2 m from the front edge of the *Spartina* marsh, in an area which has a small amount of pioneer *Spartina.* The value of 1.3 at 17 cm is much lower than the rest of the core, giving a distinctive trough in the profile. There is no particular trend in the results for the rest of the core.

Core ORF is located on the *Spartina* marsh, 15 m from the edge of the marsh in a very muddy area and has a relatively low covering of *Spartina* at about 20 %. The variability in % LOI for this core is greater than that of any core examined so far, resulting from a systematic decrease in the % LOI down the core profile.

Core ORG is situated 2 m from the edge of a creek on the *Spartina* marsh. The coverage of *Spartina* in this area is about 40 %. The graph illustrates that there is small decrease in the % LOI values to a depth of 15 cm rising again slightly to 31 cm. Below this are peaks at 36 cm, 50 cm, 69 cm and 87 cm superimposed on a slightly decreasing trend in %LOI down the core profile. The % LOI increases slightly at 97 cm.

Core ORH is located on a small hummock within the *Spartina* marsh with at least 70 % covering of *Spartina.* There is an overall reduction in the % LOI down the core profile to around 40 cm although there are small peaks at 11 cm, 16 cm and 26 cm. At the base of the core, 93 cm, the % LOI shows an increase.

Core ORJ is located beside a small tributary which feeds into a larger creek, 3 m from the core. There is a complete coverage of vegetation here, with *Spartina, Salicornia* and *Puccinellia* all present. The high deviation reported in Table 5.8 results from a large amount of variation down the core profile. The % LOI begins low but increases steadily to around 35 cm below which there is a general reduction. As with many of the cores, superimposed on the general trends are peaks and troughs in the % LOI. There is a major peak at 59 cm. Below 83 cm, the % LOI indicates an almost uniform organic content.

Core ORK is the most inland core of this series and is located on a higher area of marsh near (4 m) a creek. There is a full coverage of vegetation with some higher species present, particularly *Plantago* and *Triglochin.* There are two sets of peaks and troughs within the top 30 cm of the core. The peaks are at 9 cm and 21 cm. Below these, the % LOI steadily decrease with depth.

Overall, there is an increase in the % LOI values from the mudflat sediments to those within more vegetated parts of the *Spartina* marsh, especially where secondary species are present. Cores from the *Spartina* marsh all show a slight decrease in % LOI with depth. The majority of cores show a lack of variation down the profiles with only the occasional peak in % LOI values, suggesting that the addition of organic material to the sediment is a gradual process. Cores ORH, ORJ and ORK, the three furthest inland, and therefore the oldest parts of the study area, show the greatest amount of variation in % LOI values down the profile, indicating a different sedimentation regime associated with more continuous coverage of vegetation by species other than *Spartina.*

5.2.6 Radionuclide specific activity profiles

Each of the cores described in Table 5.7 and Section 5.2.5, was analysed for ^{137}Cs and ^{241}Am to determine the spatial distribution of radionuclides across the marsh. The results for these analyses are given in Appendix 2, Table (iii).

As with the Southwick cores there is a large degree of variation in the radionuclide specific activities within Orchardton. In the deeper sections of some cores ^{137}Cs and ^{241}Am were below the limit of detection. ^{137}Cs specific activities ranged from 5 Bq kg^{-1} to 2323 Bq kg^{-1}. ^{241}Am specific activities are generally lower than corresponding ^{137}Cs values but this situation is not nearly as prevalent as in the Southwick cores. ^{241}Am activities range from 5 Bq kg^{-1} to 1626 Bq kg^{-1}. Graphs of the specific activity profiles are given in Figure 5.7.

Core ORA, on the mudflat, shows a slight reduction in ^{137}Cs and ^{241}Am specific activities towards the base of the core. ^{137}Cs specific activities range from 125 Bq kg^{-1} to 234 Bq kg^{-1} and those of ^{241}Am from 144 Bq kg^{-1} to 309 Bq kg^{-1}. The $^{137}Cs/^{241}Am$

activity ratios are all low ranging from 0.5 to 1.0. There is a slight increase in the ratio towards the base of the core.

Core ORB obtained from a position within the *Salicornia* marsh has markedly different radionuclide concentrations and distributions from Core ORA which was obtained from the mudflat. The range of concentrations is greater in ORB with ^{137}Cs ranging from 191 Bq kg^{-1} to 1136 Bq kg^{-1} and ^{241}Am from 197 Bq kg^{-1} to 517 Bq kg^{-1}. The profiles for the top 38 cm of the core are featureless, but values increase steadily below this depth. There are dips in concentrations at 61 cm and 89 cm. This pattern is shown in both radionuclides but is more pronounced in the ^{137}Cs profile. The $^{137}Cs/^{241}Am$ ratios range from 1.0 to 3.2 with the highest values being found below 38 cm.

Core ORC was collected from the mudflat and the upper part of the core is similar to core ORA in that the radionuclide specific activities and the $^{137}Cs/^{241}Am$ activity ratios are low. Below 69 cm however, the activities begin to increase and the ^{137}Cs and ^{241}Am values diverge, giving a slight increase in the activity ratios. The maximum ratio is 1.3, well below the values shown in ORB. The ^{137}Cs specific activities ranges from 106 Bq kg^{-1} to 870 Bq kg^{-1} whilst ^{241}Am is from 114 Bq kg^{-1} to 872 Bq kg^{-1}.

ORD was also from the mudflat and has radionuclide profiles very similar to those of Core ORA except there is a slight increase in specific activities at depth. The ^{137}Cs value range from 177 Bq kg^{-1} to 449 Bq kg^{-1}. ^{241}Am values range from 213 Bq kg^{-1} to 370 Bq kg^{-1}. The $^{137}Cs/^{241}Am$ activity ratios range from 0.6 to 1.5 and the highest values are found at depth.

Core ORE is different from those described previously because the specific activities of radionuclides fall below detection limit at depth. The ^{137}Cs values range from 7 Bq kg^{-1} to 869 Bq kg^{-1} and ^{241}Am from 12 Bq kg^{-1} to 447 Bq kg^{-1}. There is a peak of both ^{137}Cs and ^{241}Am activities at a depth of 35 cm. The $^{137}Cs/^{241}Am$ ratios increase steadily towards depth until 49 cm below which ^{241}Am falls below detection limit and activity ratios cannot be calculated.

In Core ORF the radionuclide specific activities range from 19 Bq kg^{-1} to 1735 Bq kg^{-1} for ^{137}Cs and from 93 Bq kg^{-1} to 1388 Bq kg^{-1} for ^{241}Am. Both nuclides show a sub-surface peak in activity but the position of maximum activity differs for ^{137}Cs and ^{241}Am. The ^{137}Cs peak is located at 20 cm whereas the peak ^{241}Am is at 30 cm. Activities of both nuclides reduce below 30 cm with ^{241}Am being below detection limit from 51 cm to the base of the core and ^{137}Cs from 58 cm to the base. The $^{137}Cs/^{241}Am$ activity ratio ranges from 0.7 to 2.6 with the highest values coinciding with peak radionuclide concentrations at a depth of 20 - 25 cm.

Core ORG follows a similar pattern to that shown by core ORF. Values for ^{137}Cs range from 1 Bq kg^{-1} to 1504 Bq kg^{-1} with a peak in activities at a depth of 24 cm. ^{241}Am concentrations range from 5 Bq kg^{-1} to 794 Bq kg^{-1} with the peak occurring at a depth of 29 cm. Below this depth the values for both radionuclides reduce quickly. The ^{241}Am activities fall below detection limit at a depth of 51cm whereas ^{137}Cs was detectable at low levels to a depth of 60 cm. No measurements were made for the samples below this depth because the errors on the ^{137}Cs activities were very high. The $^{137}Cs/^{241}Am$ activity ratio ranges from 0.8 to 8.6. There is a peak in the ratio at a depth of 21 cm to 25 cm but the highest values occur at depth where the ^{241}Am activity is very low compared to ^{137}Cs.

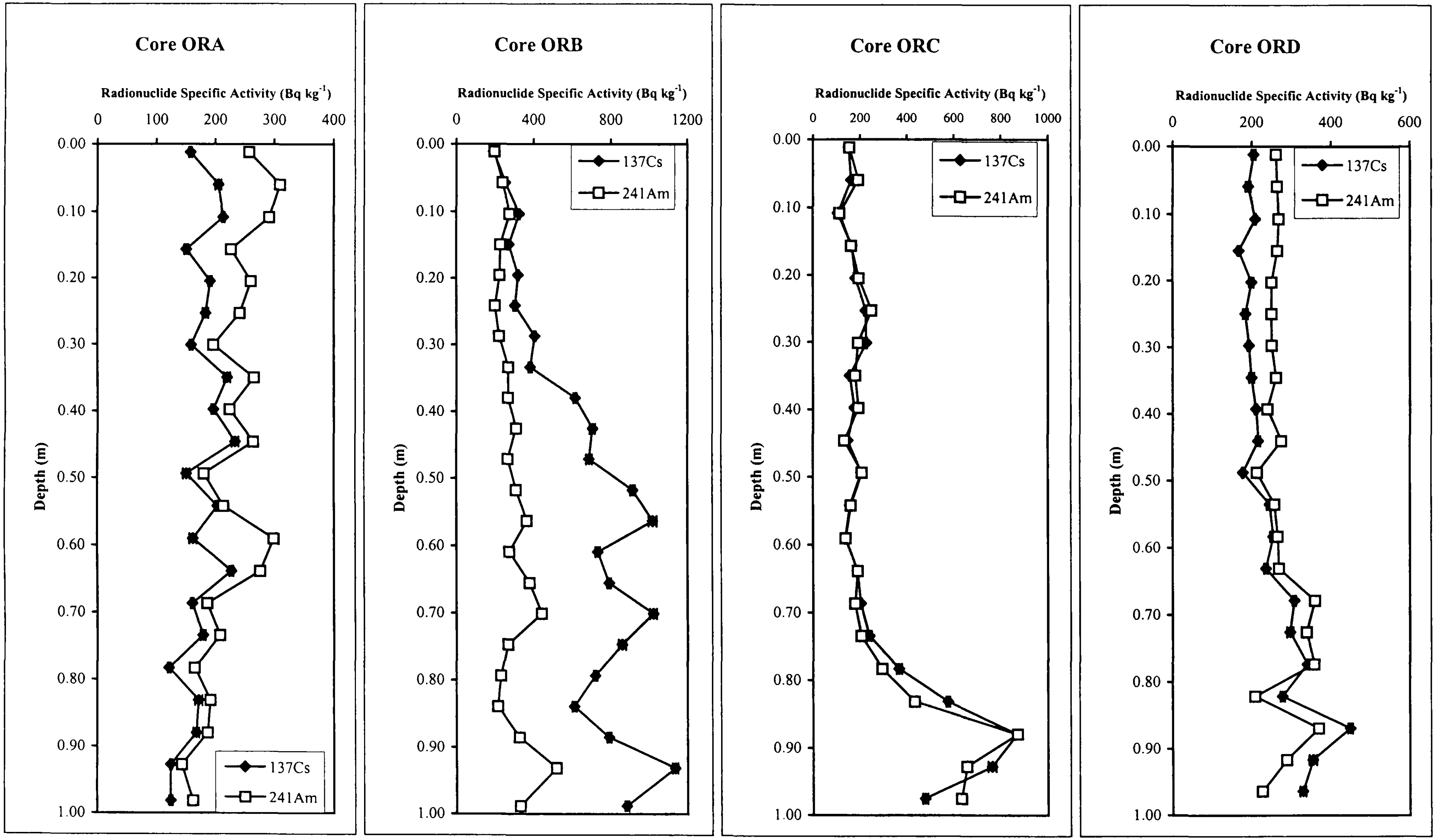


Figure 5.7 Radionuclide specific activity profiles - Cores ORA, ORB, ORC, ORD

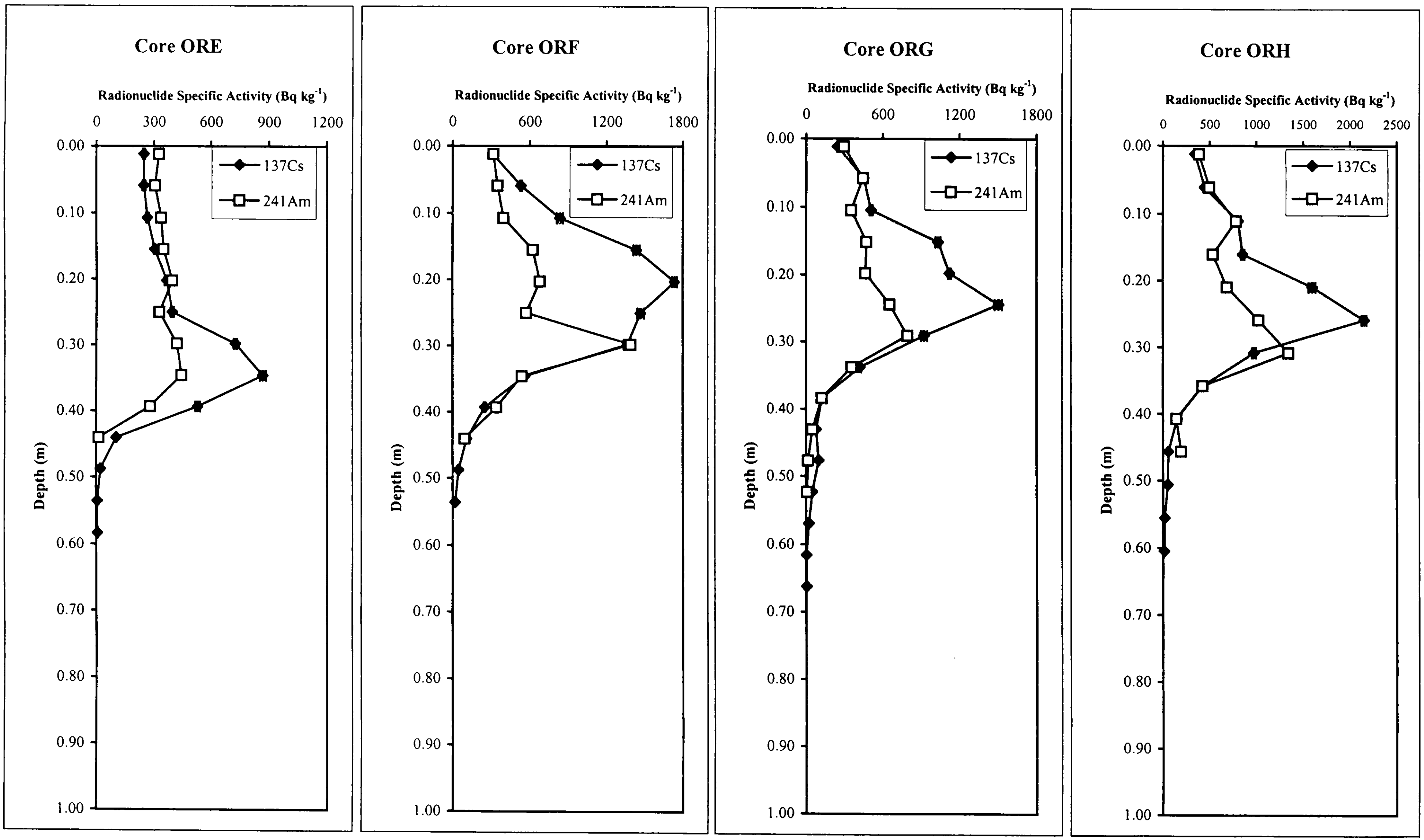
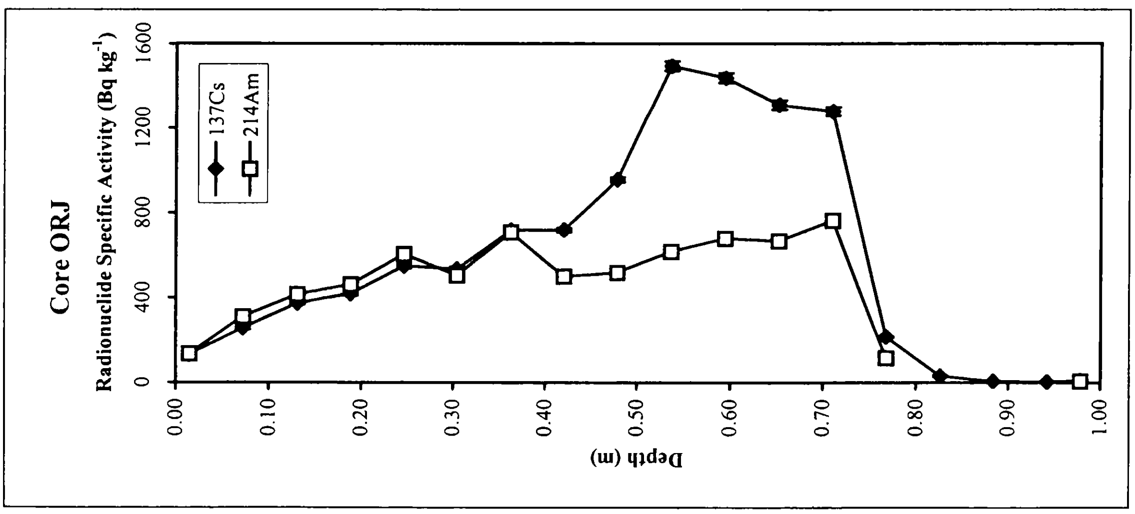


Figure 5.7 (cont.) Radionuclide specific activity profiles - Cores ORE, ORF, ORG, ORH



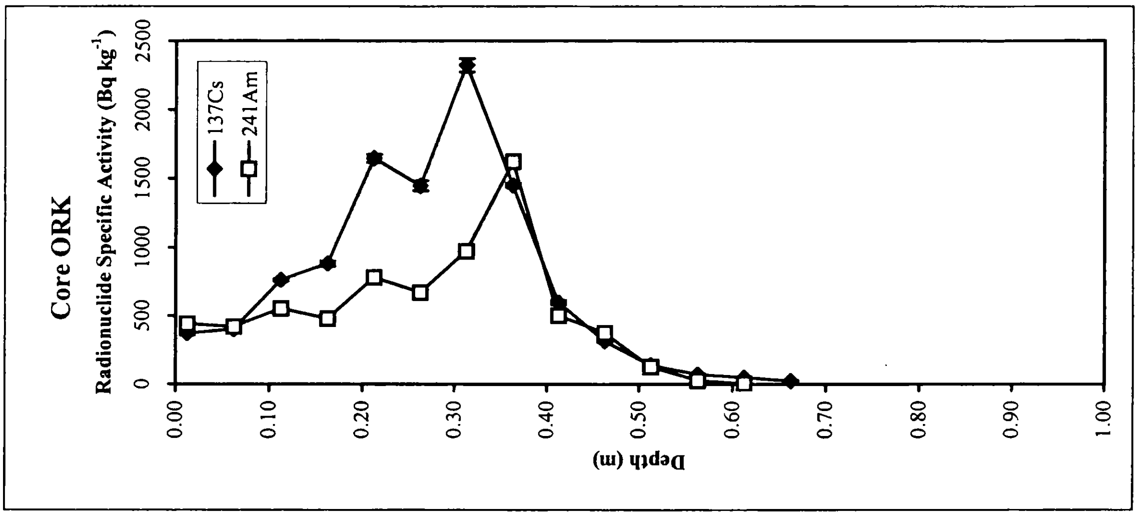


Figure 5.7 (cont.) Radionuclide specific activity profiles - Cores ORJ, ORK

Core ORH has ^{137}Cs activities ranging from 12 Bq kg^{-1} to 2150 Bq kg^{-1} with a peak value at a 26 cm. ^{241}Am concentrations range from 144 Bq kg^{-1} to 1341 Bq kg^{-1} with a peak at 31 cm. ^{241}Am activities become undetectable below 51 cm. The $^{137}Cs/^{241}Am$ ratio ranges from 0.3 to 2.3 with the peak values occurring at a depth of 20 cm to 25 cm.

Core ORJ has different profiles to those described above, with high activities of both ^{137}Cs and ^{241}Am over the depth range 50 - 80 cm rather than sharp peaks. ^{137}Cs specific activities range from 2 Bq kg^{-1} to 1495 Bq kg^{-1}. The values are very low below a depth of 83 cm. The peak values occur between 54 cm and 71 cm. The ^{241}Am specific activities range from 6 Bq kg^{-1} to 763 Bq kg^{-1}. The ^{241}Am values generally increase to a depth of 71 cm although there is a smaller peak at 36 cm. Below 71 cm activities reduce sharply. The $^{137}Cs/^{241}Am$ ratio ranges from 0.8 to 2.4 with a peak in values at 54 cm.

The radionuclide activities in Core ORK increase rapidly with depth in the top part of the core and then reduce sharply below 41 cm. ^{137}Cs concentrations range from 24 Bq kg^{-1} to 2323 Bq kg^{-1} the highest activities observed at this site. The ^{137}Cs activity peaks at 31cm. ^{241}Am specific activities range from 5 Bq kg^{-1} to 1626 Bq kg^{-1}, again being the highest values measured for this marsh. The ^{241}Am peak occurs at 36 cm. The $^{137}Cs/^{241}Am$ activity ratio ranges from 0.8 to 9.3 and has a peak coinciding with peak radionuclide activities but the maximum ratios are at the base of the core, where ^{241}Am concentrations are very low.

The three cores from the unvegetated mudflat, (ORA, ORC and ORD), all have profiles which show little variation in radionuclide activities with depth. In cores ORC and ORD there is an increase in the activities of both ^{137}Cs and ^{241}Am at approximately 87 cm depth., with the increase being more pronounced in Core ORC. Core ORB located on the *Salicornia* marsh is different from the other cores in that it exhibits radionuclides down the whole length of the core and there is a steady increase with depth.

The remaining cores all exhibit a peak in the radionuclide specific activities at depth although the position of the peak varies. Cores ORJ and ORK, which are from localities further inland than the other cores, have high radionuclide concentrations at lower depths. The depth occupied by the peak concentrations increases in the cores further inland. For example, core ORG has increased amounts of ^{137}Cs from a depth of 15 cm to 29 cm, a depth of 14cm. Core ORK has increased ^{137}Cs concentrations from a depth of 11cm to 41cm, over double the corresponding depth range Core ORG.

5.2.7 Analysis of sediment sizes within cores

A number of samples from each core were sieved and analysed using the Coulter 230LS laser particle sizer. The results from the sieving, expressed as the differential percentage (as opposed to cumulative percentage) coarser than the sieve size, are given in Appendix 2, Table (iv). The results from the analysis using the Coulter 230LS are expressed as the percentage of the sample finer than a particular size and are given in Appendix 2, Table (v).

As with the Southwick cores, direct observation of the sediment trapped by the 125 μm sieve showed it to be agglomerates of smaller particles, rather than individual particles. This and (as mentioned in section 5.1.7) the relationship between fine sediment and radionuclide concentrations (for example, Aston and Stanners, 1981, Clifton and Hamilton, 1982, Pentreath *et al,* 1984) necessitates closer investigation of the fine fraction.

Analysis of sieving results from all the cores shows that 85.07 % (standard deviation 5.5 %) of sediment is less than 125 μm and that 67.6 % (standard deviation 2.2 %) is less than 63 μm, demonstrating the very fine nature of the sediment on Orchardton as a whole. Table 5.9 illustrates this in more detail. Further analysis of the fine fraction (<63 μm) was completed using the Coulter LS 230. A summary of the mean results for each core is given in Table 5.10.

Table 5.9 shows that in all the cores, more than 60 % of the sediment is less than 63 μm. The data from the Coulter LS 230, Table 5.10, shows that 80% of the sediment is less than 63μm, except in cores from the mudflats which have coarser sediment. The cores with the greater amount of clay are those on the mature *Spartina* marsh, especially in areas which are some distance from the influence of creeks.

Core	ORA	ORB	ORC	ORD	ORE	ORF	ORG	ORH	ORJ	ORK
Mean % less than 125 μm	90.2	86.7	88.6	88.3	86.5	80.4	85.2	78.5	84.6	81.7
Standard deviation	4.0	4.0	2.8	3.6	2.3	5.0	4.0	6.5	5.1	3.5
Mean % less than 63 μm	64.9	68.9	67.2	67.7	67.9	63.3	69.4	67.4	71.3	68.1
Standard deviation	7.5	5.7	4.4	8.7	2.2	3.7	3.1	6.8	4.4	2.1

Table 5.9 Fine fraction characteristics for Orchardton cores

Core	ORA	ORB	ORC	ORD	ORE	ORF	ORG	ORH	ORJ	ORK
Mean % less than 63 μm	59.9	71.6	66.9	68.0	72.8	77.9	74.9	84.7	77.7	80.4
Standard deviation	7.2	4.2	5.9	4.9	2.3	4.5	5.3	3.7	10.4	4.0
Mean % less than 32 μm	16.3	26.9	21.9	21.6	28.5	36.4	31.7	46.4	34.7	37.8
Standard deviation	7.5	6.5	4.9	7.2	3.1	6.7	6.4	8.7	13.6	6.0
Mean % less than 16 μm	9.5	16.1	13.0	13.1	17.5	22.2	18.0	28.5	19.5	22.1
Standard deviation	4.7	4.4	2.7	5.0	1.7	3.9	4.8	5.6	7.3	3.3
Mean % less than 7.8 μm	6.1	9.6	7.8	7.9	10.1	12.2	10.5	15.8	11.0	12.4
Standard deviation	2.7	2.0	1.4	2.7	0.7	1.9	2.2	2.5	3.6	1.6
Mean % less than 3.9 μm	3.8	5.3	4.5	4.5	5.2	5.7	5.6	7.3	5.6	6.1
Standard deviation	1.5	0.5	0.8	1.2	0.3	0.6	0.5	0.7	1.3	0.5

Table 5.10 Analysis of fine fraction of Orchardton cores

Within individual cores there does not appear to be any clear pattern or trend down the length of the core but this may be because of a deficit of analysed samples.

5.3 Caerlaverock

5.3.1 Setting and historical development

Caerlaverock Merse is the largest area of continuous marsh in the Solway Firth, extending from grid reference NY 06 00 66 to NY 06 07 66. The entire Inner Solway (mudflats and saltmarshes) is designated as a Ramsar Site, a Special Protection Area under the EC Directive for the Conservation of Wild Birds (79/409/EEC), a Nature Conservation Review Site and a Site of Special Scientific Interest (SSSI) for its biological, geological and geomorphological interest (Buck, 1993). Caerlaverock is a National Nature Reserve and part of the site is a reserve operated by the Wildfowl and Wetlands Trust (WWT). Caerlaverock Merse covers 563 ha and, as would be expected with such a large area, contains marsh at various stages of development. Of particular interest is the fact that there are areas which are currently accreting sediment and areas which are being eroded. Subsequently, this study includes two sites from Caerlaverock, reflecting the different, and spatially separated, sedimentary environments. Caerlaverock can be classified as a Northern European, macro-tidal, open coast marsh which is colonised by natural *Puccinellia* vegetation and is grazed by both cattle and wildfowl (although the two study sites rarely have cattle on them).

The physiographic development of Caerlaverock marsh over time has been investigated by numerous authors (e.g. Marshall, 1960-61, 1962; Bridson, 1979; Rowe, 1978; Nelson, 1979) and the following description of the development of Caerlaverock is based on the analysis of sequential maps presented by these authors. Caerlaverock Marsh is illustrated in Figure 5.8, together with place names mentioned in the text.

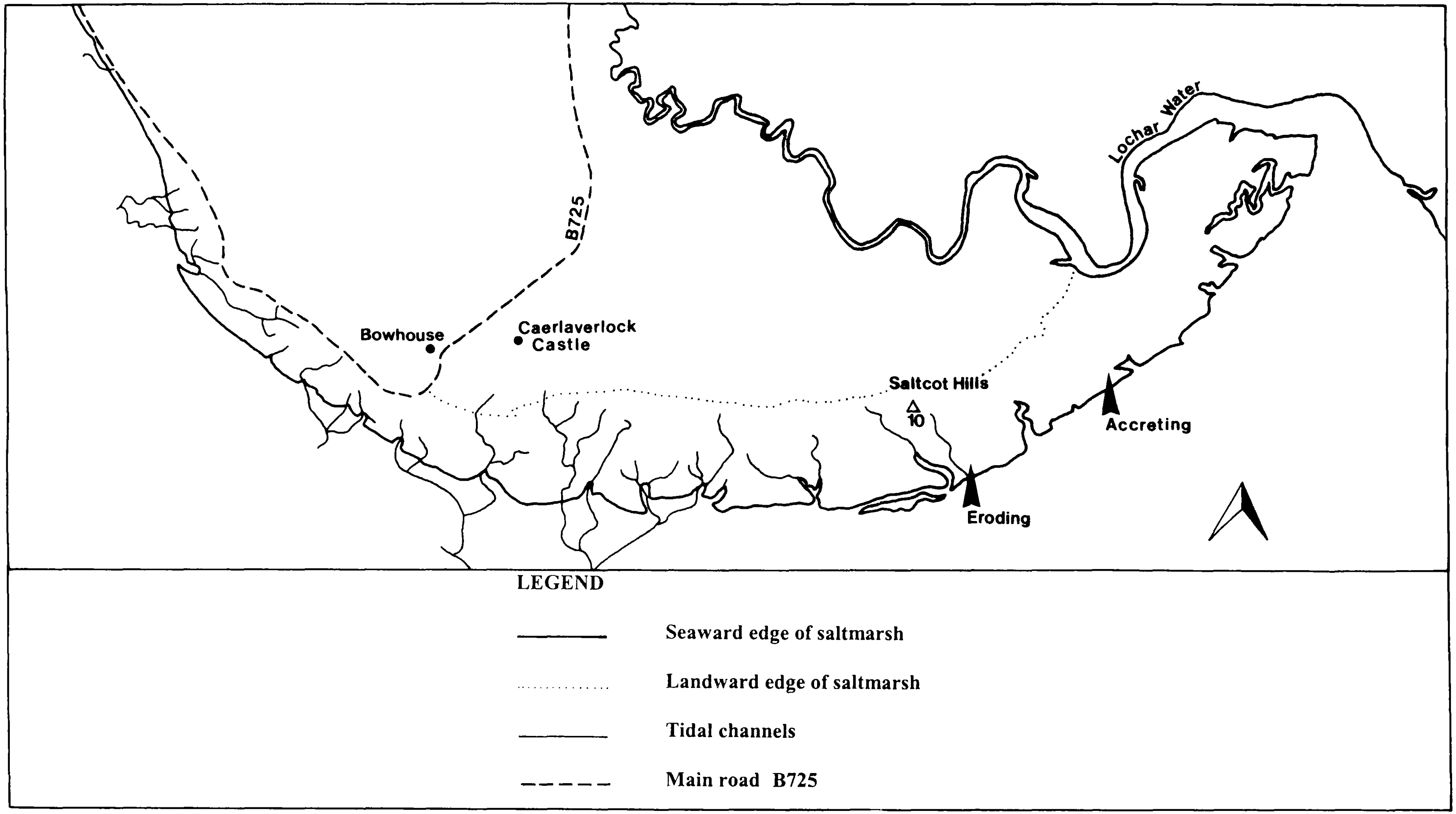


Figure 5.8 Sketch map of Caerlaverock Merse indicating location of study sites

Caerlaverock Merse fronts a two-terraced raised beach, deposited during the peak of the Holocene marine transgression, 6000-7000 years ago. Marshall (1962) considers the raised beach to in fact be old saltmarshes, since old creeks can be seen on aerial photographs. Thus the area would be better described as raised carse (Plate 5.2*).

The creeks, which resemble those on the modern marsh, can still be discerned, even though the land has under agriculture for hundreds of years (Plate 5.2). The upper marsh terrace (7-8 m O.D.) is separated from the lower one (5-6 m O.D.) by a 1.2-1.5 m high bank (Steers, 1973). The development of the Holocene and modern marsh has been possible, despite the relatively exposed position of Caerlaverock, because the area is moderately sheltered from the prevailing south-westerlies by the Carboniferous outcrop, Southerness Point, (Marshall, 1960-61).

Marshall (1962) suggests that accretion of the marsh fronting the lower raised carse terrace has occurred in 140 years (prior to the time of writing in 1962). Historical evidence shows that in the thirteenth and fourteenth centuries, the moat of Caerlaverock Castle was filled by the sea (Steers, 1973) and a map constructed in 1774 shows the extent of Caerlaverock Merse to be limited (Rowe, 1978). Extension of the marsh is attributed to the construction of a rubble wall along the western bank of the River Nith designed to straighten and confine the river for navigational purposes. The wall, constructed between 1850 and 1860 by the Nith Navigation Commission, had the effect of sheltering the Caerlaverock area from the full effects of wave and tidal currents, thereby encouraging rapid sedimentation. Three main phases of accretion can be identified: limited accretion in the lee of Saltcot Hill prior to 1856; accretion at Bowhouse Scar until 1989 and then up to 1927 to the west of the scar. The marsh reached its maximum extent during the 1920s (Morss, 1927).

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* Aerial photographs courtesy of Jane Drummond, Department of Geography and Topographic Science, University of Glasgow.

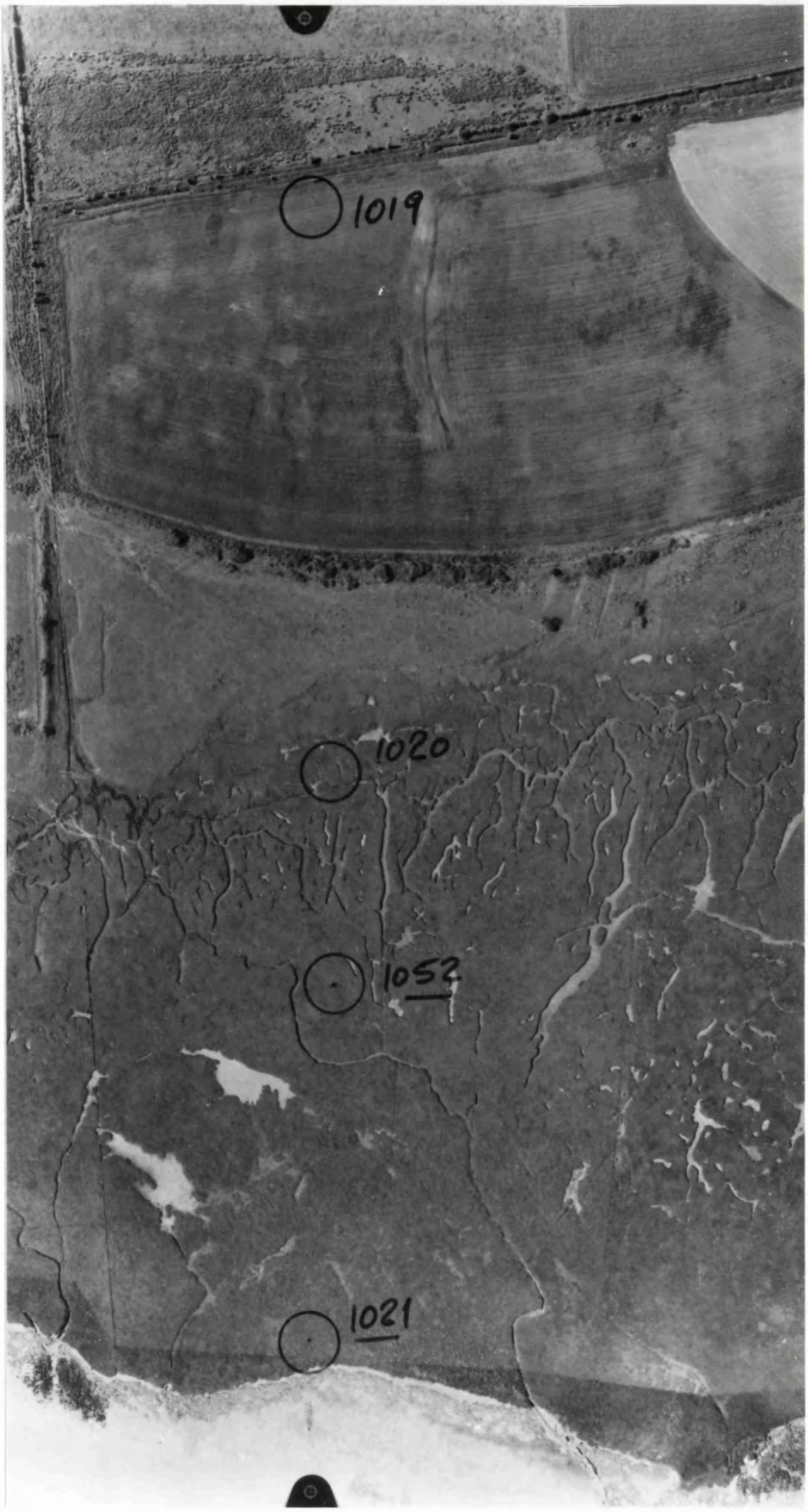

Plate 5.2 Aerial photographs illustrating raised carse deposits and old creek networks

During the 1920s the Nith channel wall collapsed, resulting in the River Nith being free to meander across its wide estuary leading to rapid erosion of the western side of the marsh. Rowe (1978) suggests an erosion rate of around 40 m per year around Bowhouse between 1946 and 1955. Bridson (1979) predicted that there would only be a small area of marsh south and west of Caerlaverock Castle in the year 2000. Recent observations of the area, however, suggest that the erosion rate has slowed somewhat and that it will be some time before this area of marsh is completely eroded.

Erosion of the marsh takes two different forms. At the eastern most point of Caerlaverock, the marsh is being eroded on its landward side as a result of fluvial action by the Lochar Water, the position of which will ultimately dictate the extent of lateral accretion in this part of the marsh. In the western part of the marsh, frontal erosion has resulted from the build-up of storm waves driven by prevailing south-westerly winds (Marshall, 1960-61).

Although the marsh is eroding on its western flank, there is accretion occurring towards the east, resulting in the progressive eastward displacement of the Lochar Water. The first diversion of the Lochar Water was the result of a gravel spit which formed near the Castle corner whilst the raised carse was active, and this process has continued (Steers, 1973). Marshall (1960-61) notes that the form of the marsh indicates a drift of sediment towards the east, the sediment being supplied from erosion of the western part and augmented by sandy material from the floor of the Solway estuary. Rowe (1978) places the transition point between the erosive and accretionary parts of the marsh around NY 046 645, but recent personal observations suggest that the transition is now further east. Marshall (1960-61) recorded the vertical accretion in the eastern part of the marsh to be 3.2 cm per year at 4.5 m OD, around 1 cm at 5 m OD and a trace at 5.2 m OD. It should be noted that although the western edge of the marsh is eroding laterally, the marsh is still accreting vertically. The amount of accretion does not however, compensate the loss by erosion (Bridson, 1979). Rowe (1978) calculated that a total of 93 ha was lost from this marsh between 1946 and 1973.

The description thus far has concentrated on broad accretion and erosion patterns over time. The following section will deal with particular geomorphological features found on Caerlaverock, some of which are located within the two study sites. As well as there being two terraces on the raised carse, there are at least three terraces located on the modern part of the marsh, fronting the raised carse. Each terrace is separated from the next by a small step varying between 30 cm and 60 cm, with each edge being more sharply defined towards the seaward edge of the marsh. While the formation of the terraces found in the raised carse areas may be partly attributed to isostatic uplift, there may be other causes. For example, Marshall (1960-61) suggests that the terraces have resulted from migration of the channels found in the estuary leading to various periods of accretion and erosion. Migration of the main tidal channels in the Solway is well known (pers. comm Martin and Hopper, 1996*) resulting from ebb conditions enhancement by the coincidence of high fresh-water inflow and easterly winds and human intervention (such as the construction of the River Nith training wall). However, Marshall also points out that the level of the lower terrace never reaches the level of the previous terrace, suggesting that there may be a fractional increase in the land level, although this has never been investigated. Plates 5.3 and 5.4 illustrates that the vertical edge of the terrace can only result from the marsh having been eroded.

* Discussion with Mr. Martin and Mr. Hopper who both fish the Solway Firth.

Plate 5.3 Terraces formed at Caerlaverock from toppling of the marsh edge

Plate 5.4 Erosion of terrace at Caerlaverock from turf stripping

The second feature of interest in the Caerlaverock Merse is the increase in the density of the creek network, peculiarly, at the landward side of the marsh. This is illustrated in Plate 5.2. First impressions suggested that the creek network was being artificially expanded by cattle trampling damage which contributes to creeks widening and expanding (Marshall, 1962). However, Plate 5.2 shows that there is an embankment (constructed at the beginning of the nineteenth century (Marshall, 1960-61)) at the landward edge of the marsh coincident with the edge of the raised carse terrace. This has the effect of damming the drainage from creeks originating on the raised terraces, thereby reducing the amount of water draining into the modern creeks and consequently reducing their erosive power. In addition to this, the accretion of the modern marsh, already shown to be very rapid, may be such that impeded creeks cannot maintain the same pace as the surrounding marsh development. These factors will result in many of the creeks being unable to erode to a sufficient depth through the marsh to allow drainage into the Solway estuary. Only the larger creeks will be able to do this and as Plate 5.2 shows, there are only a few of these. The creek network feeding these larger creeks has become more dendritic and lateral creeks have developed to deliver water to the head of the main creeks. The 'youthfulness' of these creeks is suggested by the fact that they are much shallower than those which extend through the whole width of the marsh.

The two study sites chosen, illustrated in Figure 5.8, reflect the differences between those parts of Caerlaverock which are being eroded and those which are currently accreting sediment. The two sites will be dealt with separately.

ERODING SITE

5.3.2 Geomorphology, vegetation and recent changes in the eroding study site

A map of the geomorphology of the study site is shown in Map 3a and a map of the vegetation and recent changes is shown in Map 3b. The study site occupies an area of 4800 m^2 and is located on the lowest of the modern terraces described above. The edge of the next terrace is located 25 m north of the study site and is identified by a 30 cm step. The study site is shown in Plate 5.5*. There are three distinct parts to the marsh: high marsh; eroded marsh edge and the mudflat.

Plate 5.5 Aerial photograph illustrating eroding site at Caerlaverock

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* Aerial photographs courtesy of Jane Drummond, Department of Geography and Topographic Science, University of Glasgow.

5.3.2.1 High marsh

The majority of the marsh has a dense cover of vegetation consisting of species such as *Festuca, Plantago maritima, Glaux maritima, Aster, Puccinellia* and *Salicornia.* The percentage of the pioneer species *Puccinellia* increases towards the front of the marsh but it never exists on its own. This suggests that the marsh is mature and is only covered by the tide during high spring tides or storms. The absence of other species which are generally found on high marsh areas within the Solway, such as *Halimione portulacoides* and *Limonium vulgare*, is attributed, by Marshall (1961-62), to grazing.

The prominent feature, compared to either Southwick or Orchardton, is the significant number of saltpans. The linear shape of the majority of the pans suggests that they may be originally channels which have become blocked. This is also indicated because, while most of the pans are around 20 cm lower than the vegetated marsh surface, some parts of the pan network are up to 0.5 m deep. Some of the pans are devoid of vegetation while others are colonised by *Puccinellia* and often *Aster.*

5.3.2.2 Eroded marsh edge

The edge of this part of the marsh is quite dramatic because there are two actively eroding terraces. The first cliff (indicated as (1) in Map 3a), around 40 cm deep, gives way to a terrace above which has been stripped of vegetation and turf. The width of this unvegetated terrace varies, with some parts being in excess of 8 m. The second cliff, (2), varies in height but is generally lower than the first cliff. Many eroded blocks lie at the base of the cliff having been eroded directly from the unvegetated terrace above.

5.3.2.3 Mudflat

The mudflat in front of the marsh has a very diverse nature and may represent an area which has recently had marsh eroded from parts. It is now, however, also a site of active sediment accumulation. Many blocks are present on the mudflat which have been eroded from the marsh and some of these are being disaggregated by wave and tidal processes. The most active site of disaggregation is immediately in front of the marsh cliff where waves on the incoming tide exert their greatest force as they break on the front of the marsh. The sites of new accumulation are generally some distance from the edge of the marsh. The presence of blocks may encourage the deposition of sediment. These areas increase in height and are colonised by new pioneer vegetation. It is likely that the seeds for colonisation come from the blocks, many of which, still have original marsh vegetation attached. The primary colonist is *Puccinellia* and once the height of the mudflat increases, *Aster* is also present. *Salicornia* occurs, although it is not a dominant coloniser.

One creek on this site is approximately 6 m wide at the front of the marsh and reduces inland to a width of less than 0.5 m. The depth of this creek at its maximum is around 1 m but this also reduces inland along a highly sinuous route. At the head of each creek branch is a pan, which is separated from the creek by a knickpoint. Within the creek there are a large number of blocks which have been eroded from the sides. These blocks are often very large which suggests that bank erosion is via undercutting. The incoming tide flows very quickly into the creek and erosion, undermining the sides of the bank, occurs. Eventually, the weight of the material lying over the undercut is such that the side of the bank shears and collapses into the creek.

Pans also occur, the deepest parts of which often lead to a small creek which acts as the exit point for water from the marsh. Within the mudflat two smaller channels exist, extensions of the main creek and smaller pan.

This part of the marsh is inundated by the tide in two ways. Firstly, water moves up the creek and during exceptional tides and over banks onto the marsh. This is the same method as shown at the other sites already mentioned. Secondly, and perhaps more importantly given that the creek does not extend far into the marsh, tidal waters inundate the marsh over the fronting terrace. On Southwick and Orchardton, the incoming tide is constrained within a tidal channel rather than, as in this case, moving across the extensive mudflat. As a result, the long fetch attained by the incoming waves allows greater energy to be expended than at the other two sites, accounting for the erosion currently occurring.

Of the marshes described so far, Caerlaverock shows the most change over the study period. The vegetation turf and cliff (1) eroded by at least 1 m in three years and in some parts by as much as 4 m. The second cliff did not erode as much, with the greatest amount of erosion being around 2 m. The width of the creek increased slightly over the study period. In addition to the erosion, there has been an expansion in the amount of primary colonisation occurring on the mudflat.

The position of the pans has not changed but in some cases there is an increased amount of vegetation within them.

5.3.3 Sedimentation in the eroding study area

The location of the plates used to establish sedimentation patterns and rates across the study sites are shown in Map 3a and the calculated sedimentation rates (cm y^{-1}.) are given in Appendix 3, Table (i) with a summary in Table 5.11.

There is a wide range of sedimentation rates on this site: the lowest rate being -16.5 cm y^{-1} and the highest 10.2 cm y^{-1}.

A number of plates were lost by erosion during the first few months because of their proximity to the edge of the marsh, although initial investigations of the site did not suggest such aggressive erosion of the marsh. Some of the plates were replaced (labelled as #a in Table 5.11) and the rates calculated from the new date. Despite care in the location of new plates, some of them were again lost by erosion. While buried plate method is appropriate in principle for studying eroding marshes, more time is needed to assess the rate of frontal erosion, so that plates can be positioned more strategically. The fact, however, that some plates were lost, provides additional information to the extent of lateral erosion occurring on this part of the marsh.

Plate	Position on marsh	Accretion Rate (cm y^{-1}.)
1	High marsh	1.6
2	High marsh - pan edge	2.6
3	High marsh - pan edge	2.4
4	High marsh	2.2
5	High marsh	3.0
6	Pioneer marsh - pan edge	3.8
8	High marsh	2.7
9	Marsh edge	-16.5
9a	Marsh edge - stripped turf	-2.5
10	Marsh edge	*
10a	Marsh edge	*
11	Marsh edge	*
11a	Creek edge	*
12	Creek edge - stripped turf	-1.1
13	Creek edge	*
13a	Marsh edge - stripped turf	-2.6
14	High marsh	1.0
15	Marsh edge - stripped turf	-8.0
15a	Marsh edge - stripped turf	-3.8
16	Marsh edge - stripped turf	*
16a	Marsh edge - stripped turf	-3.0
17	Mudflat	10.2
18	Pioneer marsh - *Puccinellia*	*
19	Mudflat	9.8
* Unable to calculate (see text)		
Note: there is no Plate 7		

Table 5.11 Summary of Caerlaverock (eroding site) plate results

On all parts of the high marsh, accretion occurs. Plate 6 indicates the highest sedimentation rate on the high marsh at 3.8 cm y^{-1}. This plate is located beside the edge of a pan which is being colonised by *Puccinellia.* The sedimentation rates on the high marsh range from 1.0 cm y^{-1} to 3.0 cm y^{-1}. Plate 1 and Plate 4 are the furthest inland and are both at least 2 m from the edge of the pan network. These plates have rates of 1.6 cm y^{-1} and 2.2 cm y^{-1}, respectively. At a similar distance inland but located on the edge of a large pan are Plates 2 and 3 which indicated very similar rates of 2.6 cm y^{-1} and 2.4 cm y^{-1}.

Plate 5, 20 m from the marsh edge and 1 m from the edge of a pan has a sedimentation rate of 3.0 cm y^{-1}. Plate 8 is also 20 m from the marsh edge, but not near a pan and has a lower rate of 2.7 cm y^{-1}.

From the results it would appear that plates located near to pans and to the seaward edge of the marsh have slightly higher sedimentation rates.

The only other areas of sedimentation are on the mudflat, where the greatest accretion rates are shown. Plates 17 and 19 gave sedimentation rates of 10.2 cm y^{-1} and 9.8 cm y^{-1} respectively, but for both of these only one set of measurement was taken because the plates could not be relocated for a second set. It is not clear whether these were eroded away or where buried too deeply to by relocated, but the latter is more likely, given that the pegs on the mudflat, used to delineate the site, were almost buried by sediment.

Almost all of the plates positioned on the edge of the marsh were eroded away with the exception of Plate 9. This plate, which was initially buried slightly deeper than the others, survived the vegetation turf being stripped from the marsh edge. The -16.5 cm y^{-1} erosion rate is perhaps misleading because it is likely that the turf was stripped off during one event, either an extreme high tide, or a storm. Plates 10, 10a, 11, 11a, and 16 were all lost by erosion so it was not possible to establish sedimentation rates at these points.

Five plates (9a, 13a, 15, 15a, 16a) were located on the stripped turf terrace at the front of the marsh and again some erosion rates were recorded. These are -2 5 cm y^{-1}, -2.6 cm y^{-1}, -8.0 cm y^{-1}, -3.8 cm y^{-1} and -3.0 cm y^{-1} respectively. Although these rates are significant, they demonstrate that the rapid removal of the vegetation turf is followed by a slower erosion rate. This pattern of erosion is also illustrated on Map 3a which shows that the extent of erosion on the terrace with no vegetation is less that that where turf stripping is occurring.

Plates 11 and 13 were located on the bank edge of the main creek and both were eroded away. Plate 12, also located near the edge of the creek on the terrace with stripped turf, survived and a sedimentation rate of -1.1 cm y^{-1} was calculated. This rate of erosion is lower than the other plates, mentioned above, which are also on the stripped turf terrace, due to the relatively sheltered position of the terrace within the creek.

There is a significant amount of erosion occurring at the front of this part of Caerlaverock marsh but, despite this, there is also vertical sedimentation of the marsh surface. The greatest amount of sedimentation appears to be occurring on the mudflat and in those areas of the high marsh which are distant from locations of wave impact on the front of the marsh. Sedimentation rates are also higher in areas close to saltpans.

5.3.4 Determination of organic content of sediment within the eroding marsh

Determination of the organic content of saltmarsh sediment at Caerlaverock was investigated in the same manner as described for Southwick and Orchardton. The locations of the cores excavated at Caerlaverock are described in Table 5.12 and illustrated in Map 3a. The results of the analyses, given as percentage Loss on Ignition (% LOI) are in Appendix 3, Table (ii) with summary statistics presented in Table 5.13.

Core	Location
CLA	Mudflat
CLB	Terraced with stripped vegetation turf
CLC	Edge of vegetated saltmarsh
CLD	High marsh – 24 m inland from edge of marsh
CLE	High marsh – 44 m inland from edge of marsh
CLF	Edge of vegetated marsh – 3 m from creek bank
CLG	High marsh – 25 m inland
CLH	Edge of vegetated marsh
CLJ	High marsh – 25 m inland
CLK	High marsh – 45 m inland, next to pan

Table 5.12 Core locations on Caerlaverock eroding site

Core	% LOI	
	Range	Mean and standard deviation
CLA	1.2 - 4.0	2.3 +/- 0.65
CLB	1.4 - 6.2	2.8 +/- 1.33
CLC	1.2 - 2.5	2.6 +/- 0.95
CLD	3.3 - 9.3	3.3 +/- 1.89
CLE	0.8 - 13.7	3.4 +/- 2.41
CLF	1.2 - 8.1	2.7 +/- 1.33
CLG	1.4 - 7.6	3.5 +/- 1.38
CLH	1.6 - 7.1	3.4 +/- 1.38
CLJ	1.0 - 6.1	2.8 +/- 1.23
CLK	1.0 - 9.1	3.1 +/- 1.84

Table 5.13 % LOI summary statistics for Caerlaverock eroding site

Graphs of each core profile are presented in Figure 5.9. The % LOI values across the whole site range from 0.8 % to 13.71 %.

Core CLA is located on the mudflat, 15 m from the front of the marsh. The top of the core to 40 cm has a series of peak % LOI values, although the percentage difference is not great. Values then become very similar to 60 cm. A large peak in values exists between 60 and 70 cm and at 91 cm.

Core CLB is located on the terrace at the edge of the marsh which has been stripped of turf. The top of the core has the highest % LOI but this steadily reduces to 41 cm. Below this depth the % LOI does not vary greatly, although there is a slight increase at the base of the core.

Core CLC is located less than 1 m from the edge of the marsh. The % LOI values generally reduce towards 44 cm, although there is a small peak in values around 10 cm depth. A major rise in the % LOI occurs deeper in the core at 45 cm, peaking at 52 cm. There is then a gradual decrease in values towards a low point at 78 cm. Below this point the % LOI remain steady with a very slight increase at the base.

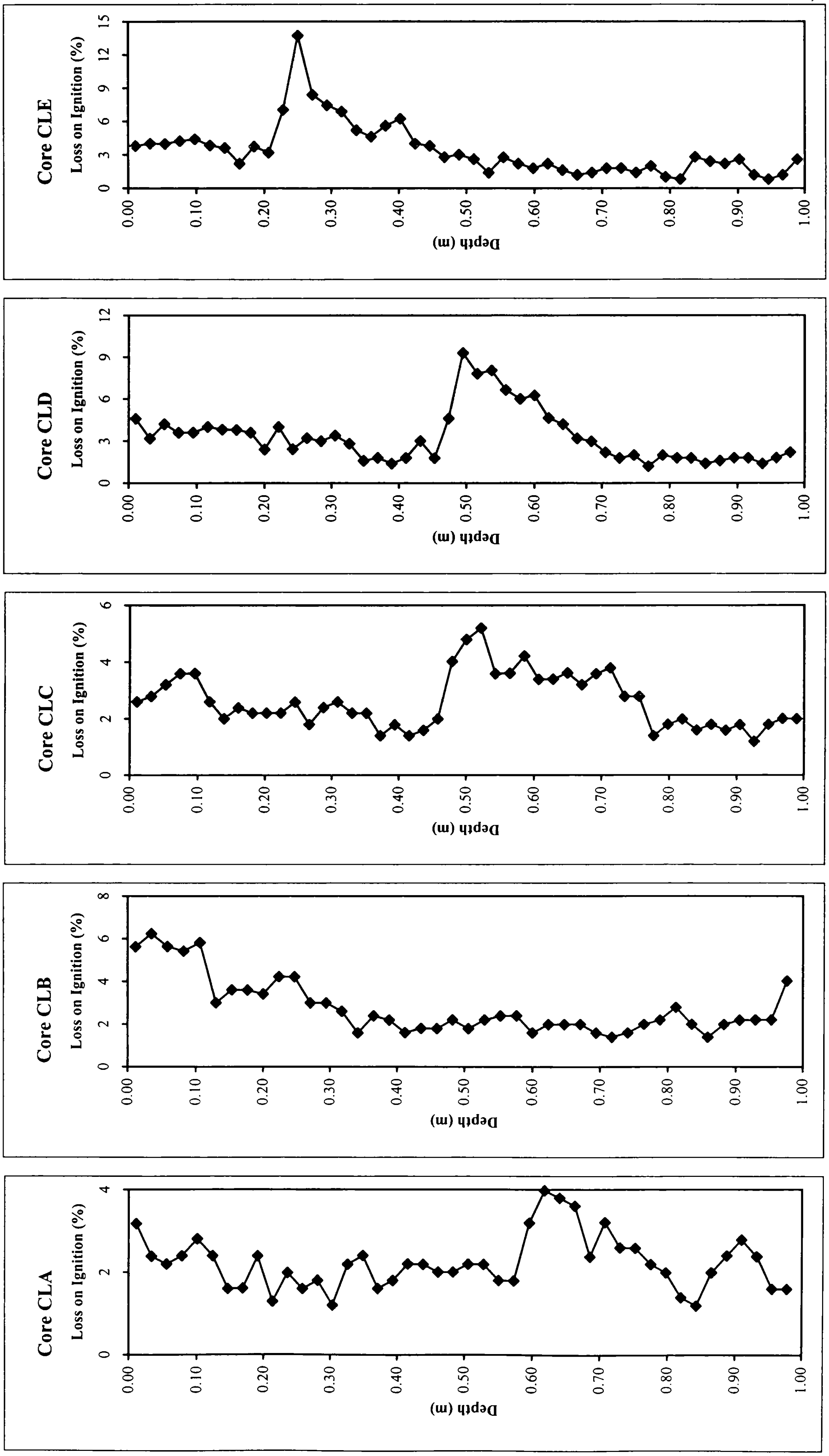


Figure 5.9 Percentage Loss on Ignition - Cores CLA, CLB, CLC, CLD, CLE

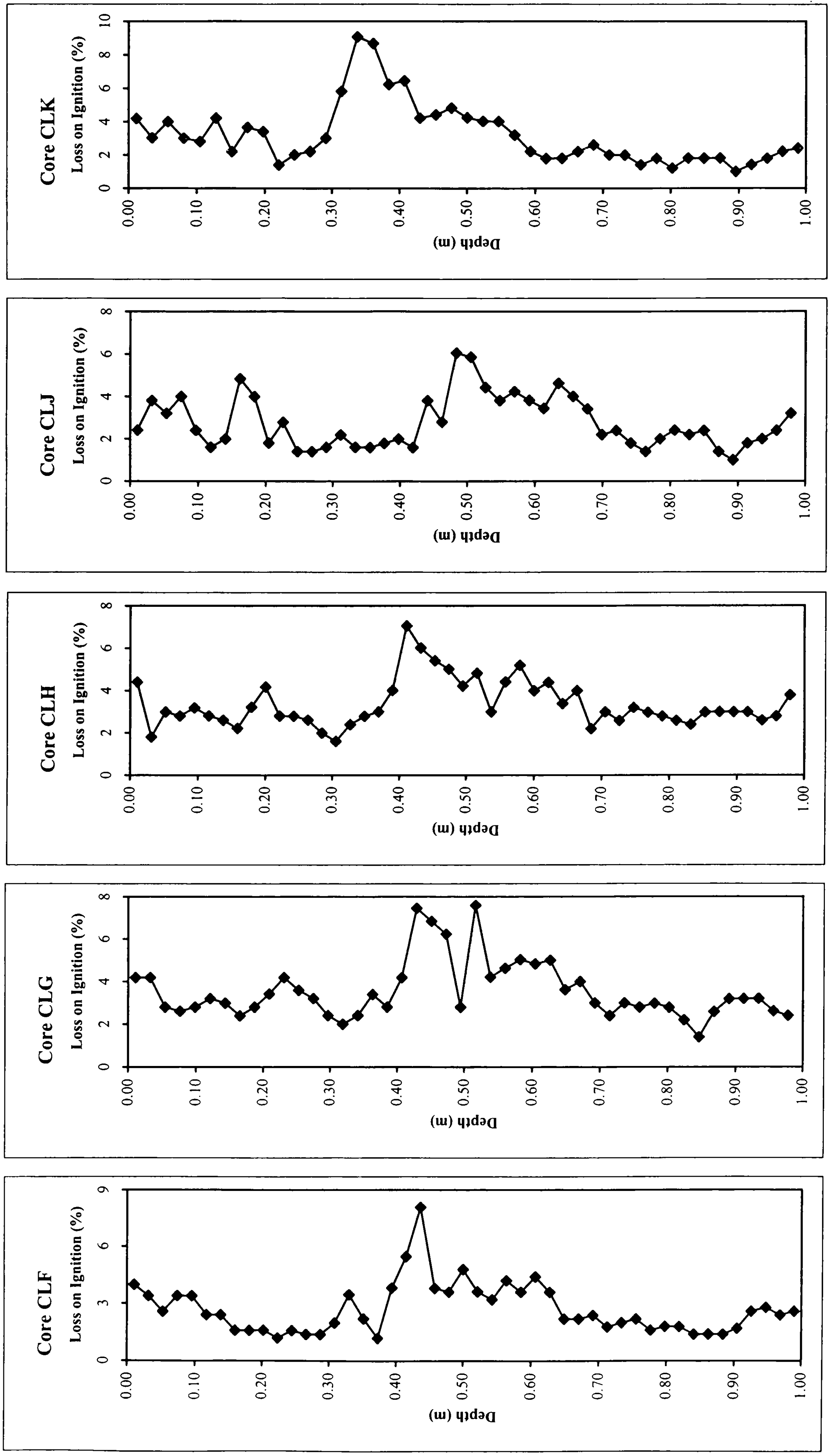


Figure 5.9 (cont.) Percentage Loss on Ignition - Cores CLF, CLG, CLH, CLJ, CLK

Core CLD, located 20 m inland front the marsh edge is comparable to Core CLC because it also contains a peak in % LOI values at depth. The profile shows that the % LOI values at the top of the core are quite high gradually reducing to a depth of 45 cm. There is then a sharp increase in values (in the same manner as CLC), with a peak at 49 cm. The values then reduce to a minimum at 78 cm depth. The peak value in this core is 4 % higher than the peak value in CLC.

Core CLE, located 40 m inland also mirrors the pattern described the previous two cores. Values in this core are high at the top of the core but increase sharply at 21 cm, peak at 25 cm depth and reduce to a minimum at 53 cm depth. The peak value of 13.7 % is the highest observed for this marsh. Below 53 cm, the % LOI shows little variation, although there is a slight elevation in values between 84 and 90 cm.

Core CLF is located near the edge of the marsh and is 3 m from the bank of the main creek in the site. This core profile also follows the general pattern described in the previous cores but the peak is not as well defined. Values are relatively high at the top of the core, and gradually reduce to a minimum at 37 cm. They then increase to a peak at 44 cm and reduce to the pre-peak level at 65 cm depth. Values gradually reduce towards the base of the core, with a slight increase evident at 93 cm.

Core CLG was obtained from a position in the middle of the study site, around 25 m inland from the edge of the marsh. The profile in this core begins the same as the others in that there is a decrease in the % LOI from the top of the core to a low point at 38cm. Superimposed on this general trend is a peak at 23 cm. Below this the values increase to a peak at 43 cm, then decrease rapidly to a minimum at 49 cm before increasing again to the highest value of 7.6 % at a depth of 52 cm. The values then reduce again towards the base of the core to a depth of 85 cm. Below this there is a slight increase in values.

Core CLH is located near the edge of the marsh and, once again, follows the pattern of most of the cores at this site. The % LOI values begin relatively high and exhibit small variations to a depth of 39 cm. The values increase to a maximum at a depth of 41 cm and then reduce again with increasing depth. There is a small increase below 96 cm.

Core CLJ is located 25 m from the edge of the marsh. The values exhibit some variation in the top 25 cm of the core. The % LOI increases sharply at 42 cm with the peak values of 6.1 % occurring at a depth 48 cm. The values then reduce, as with the other cores, to a depth of around 90 cm, below which there is a slight increase.

Core CLK, located 45 m inland has a variable % LOI in the top 20cm of the core although the general pattern shown in the other cores is again repeated at depth. The values begin to increase at a depth of 29 cm, peaking at 34 cm. They then reduce to a depth of 60 cm. Values again increase at the base of the core, below 90 cm.

On the marsh as a whole there is a slight increase in % LOI values from the mudflat sediments to sediments located at increasing distances from the front of the marsh. It must be pointed out, however, that calculated mean values for the cores from this marsh are not very meaningful because of the organic peaks found at depth in most of the cores. As a consequence of these peaks the profiles of organic content for these cores are quite different to cores described for other sites.

An interesting observation about the organic peak in the cores is that the depth which the peak occupies in each core is similar. For example in Core CLD the peak % LOI values are present from 45 to 77 cm, a depth increment of 32 cm. In core CLE the peak organic sediment is from 21 cm to 43 cm, also a total depth of 32 cm. The total depth occupied in cores CLC, CLF, CLG, CLH, CLJ and CLK is 32 cm, 28 cm, 33 cm, 29 cm, 28 cm and 32 cm respectively. The consistency in the dimensions of the peak suggests that the mechanism by which it has formed, is the same for all the cores.

The absolute depth at which the peak organic values occur is also of interest. The cores at the furthermost points inland, Cores CLE and CLK, have peak organic depths at 25 cm and 34 cm respectively. The depth of the peak then increases towards the front of the marsh. The cores located around 25 m inland from the front of the marsh, that is Cores CLD, CLG and CLJ, show peak organic values at 49 cm, 43 cm and 48 cm. The cores at the front of the marsh have peak organic values at depths of 52 cm, 44 cm and 41 cm. These results suggest that the amount of sedimentation which has occurred since the event (or period of events) causing the peak in organic content varies across the marsh.

The greatest amount of sedimentation has occurred in the central parts of the study site, i.e. the depth of the peak is greatest, with lower amounts of sedimentation in areas further inland and at the very front of the marsh.

5.3.5 Radionuclide concentrations across the eroding study area

Of the cores described in Table 5.12, only five were analysed for radionuclide concentration, in order to assess the variability in contamination with distance inland and with depth. The five cores, CLA, CLB, CLC, CLD and CLE represent a transect from the mudflat to the high marsh. The cores were initially dissected into 2 cm increments (for the organic content analysis) but for logistical reasons the increments were re-combined into larger increments for the radionuclide analysis. The impact of sampling strategy is discussed in Section 4.7.4 where it is demonstrated that with the use of larger increments, while fine details in the radionuclide profiles are lost, the gross pattern of change along the length of the core remains clear. It was felt, for the purposes of this investigation, that this was an appropriate level of detail to determine the effect of distance from the front of the marsh on the radionuclide profiles. The utilisation of these two strategies, analysing fewer cores at a coarser sampling increment, dramatically reduced the number of samples requiring analysis.

The results for those cores analysed are given in Appendix 3, Table (iii). The range of detectable radionuclide specific activities is 2 Bq kg^{-1} to 1079 Bq kg^{-1} for ^{137}Cs and 17 Bq kg^{-1} to 390 Bq kg^{-1} for ^{241}Am. As with the Orchardton cores, ^{137}Cs and ^{241}Am activities fell below the limit of detection in cores from Caerlaverock. The profiles are illustrated in Figure 5.10. It should be noted that the depths indicated in the tables, graphs and reporting below (including the results reporting for the accreting site of Caerlaverock), are average depths for a particular sampled core increment. For example if a particular peak lies at a depth of 39 cm, this means that the peak actually occupies some point between 34 cm and 43 cm, because the core increment sampled covers an adjusted depth of 9 cm.

Core CLA is a very featureless core with very little change in either ^{137}Cs or ^{241}Am down the profile. ^{137}Cs specific activities range from 2 Bq kg^{-1} to 118 Bq kg^{-1} and the specific activities of ^{241}Am range from 51 Bq kg^{-1} to 73 Bq kg^{-1}. The ^{137}Cs/^{241}Am ratios for the profile are very consistent ranging from 1.6 to 1.8.

Core CLB, located on the marsh terrace devoid of turf, is different to any other core investigated because the higher radionuclide activities are at the top of the core. The ^{137}Cs specific activities range from 1079 Bq kg^{-1} at the top of the core to 15 Bq kg^{-1} at around 33 cm. Below this depth ^{137}Cs is undetectable. For ^{241}Am the range is from 390 Bq kg^{-1} to 25 Bq kg^{-1}, with the peak value being at a depth of around 7cm. The is no detectable ^{241}Am below a depth of 16 cm. The ^{137}Cs/^{241}Am activity ratio is high at the top of the core at 3.2, with a reduction to 1.7 at 7 cm and an increase at 24 cm to 6.3.

Core CLC presents a similar profile to those observed for Southwick and Orchardton. The range of ^{137}Cs specific activities is from 29 Bq kg^{-1} to 521 Bq kg^{-1} and the ^{241}Am range is from 36 Bq kg^{-1} to 191 Bq kg^{-1}. The pattern shown in this profile can be divided into three parts. The top 15 cm has specific activities above 100 Bq kg^{-1} for ^{137}Cs and above 50 Bq kg^{-1} for ^{241}Am, resulting in a ^{137}Cs/^{241}Am activity ratio less than 2.0. The area between 15 cm and 40 cm has reduced ^{137}Cs and ^{241}Am specific activities but higher ratios, at 2.5. The sediment below 40 cm has peak radionuclide specific activities, and a peak ratio value. The peak ^{241}Am specific activity occurs at a lower depth than that of ^{137}Cs.

Core CLD is located 25 m inland from the edge of the marsh. The ^{137}Cs specific activity ranges from 10 Bq kg^{-1} to 426 Bq kg^{-1} while that for ^{241}Am is from 17 Bq kg^{-1} to 147 Bq kg^{-1}. There is a slight reduction in activities from the top of the core to a depth of 40 cm where the values rise to the maximum values. The highest ^{137}Cs/^{241}Am activity ratio coincides with the peak radionuclide concentrations.

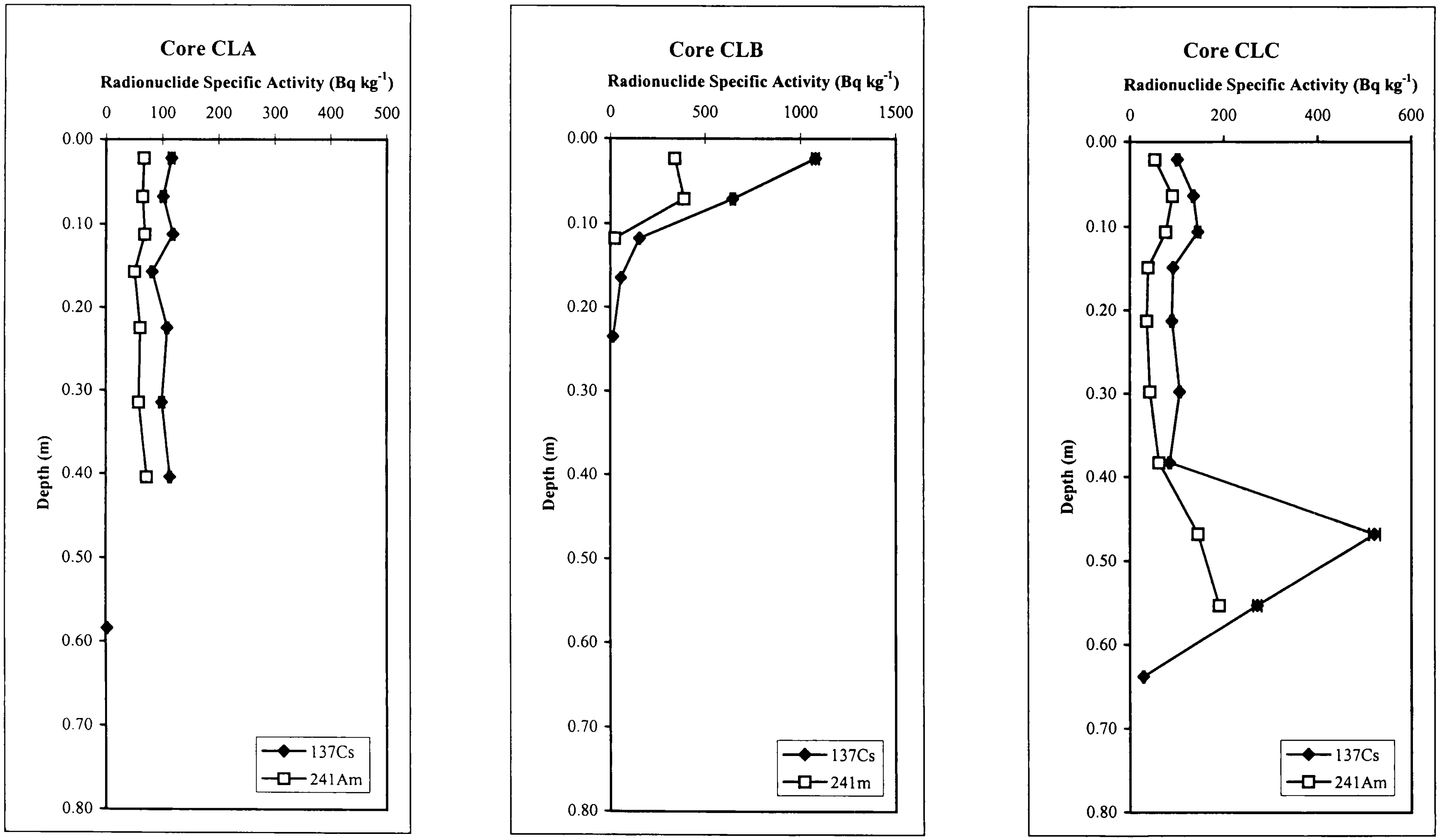
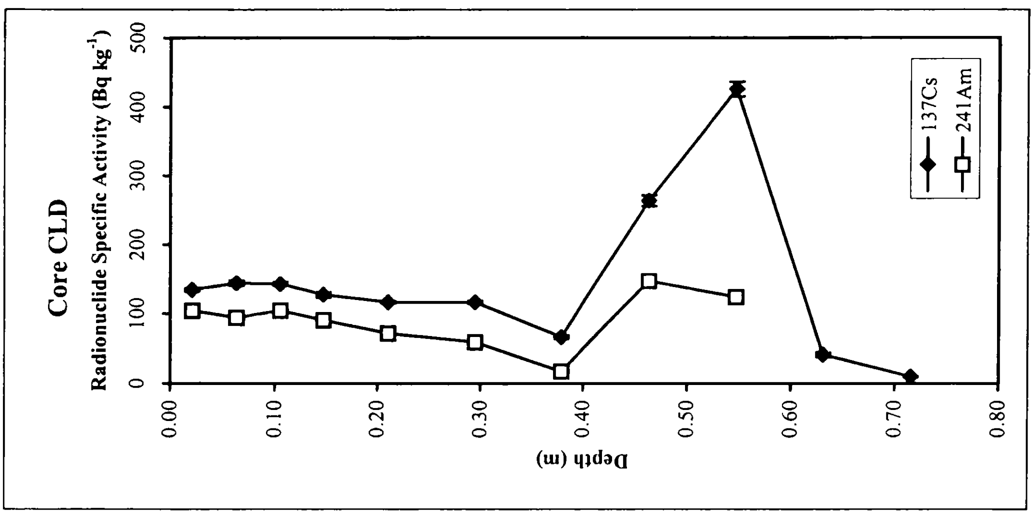


Figure 5.10 Radionuclide specific activity profiles - Cores CLA, CLB, CLC



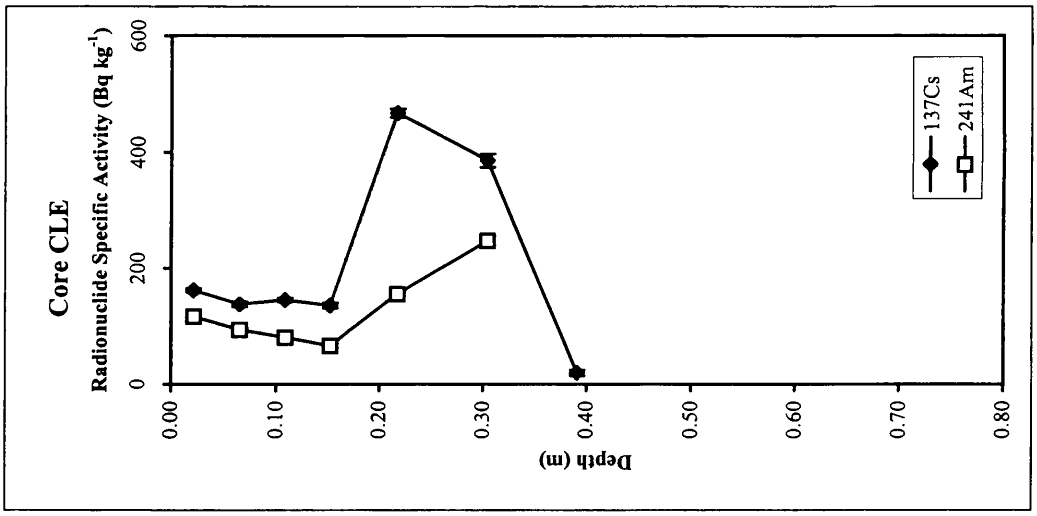


Figure 5.10 (cont.) Radionuclide specific activity profiles - Cores CLD, CLE

Core CLE, located 45 m inland from the edge of the marsh, has a range of ^{137}Cs specific activities from 19 Bq kg^{-1} to 468 Bq kg^{-1} and ^{241}Am from 66 Bq kg^{-1} to 248 Bq kg^{-1}. As with core CLD, there is a slight reduction in radionuclide activities from the top of the core to a depth of 20 cm, thereafter the specific activities of both ^{137}Cs and ^{241}Am increase. The peak ^{137}Cs activities occur at a depth of 22 cm with the ^{241}Am peak occurring slightly deeper at 30 cm. There is no detectable ^{137}Cs or ^{241}Am below 40 cm.

In summary, the mudflat core shows very little variation down its depth. The cores located on the marsh all have peak radionuclide activities at depth however, the location of the peak, varies. Cores CLC, CLD and CLE are on vegetated parts of the marsh with CLE being the furthest inland. The peak in this core is at the shallowest depth. Core CLD has the peak occurring at the deepest position with the peak in CLC occurring slightly higher than in CLD.

Core CLB appears anomalous because the peak radionuclide concentrations occur at the top of the core.

5.3.6 Analysis of sediment sizes within cores from the eroding marsh

Samples from each of the cores analysed for radionuclide concentrations were sieved and analysed using the Coulter 230LS laser particle sizer. The results from the sieving expressed as the percentage of sediment coarser than the sieve size are given in Appendix 3, Table (iv). The results from the Coulter 230LS analysis are expressed as the percentage of the sample finer than a particular size and are given in Appendix 3, Table (v).

As with Southwick and Orchardton (see Section 5.1.7), the finer particles received greater consideration. Analysis of the sieving results from all the cores shows that 88.3% (standard deviation 5.0 %) of sediment is less than 125 μm and that 47.8 % (standard deviation 3.8 %) is less than 63 μm demonstrating the fine nature of the sediments at this site. Table 5.14 illustrates this in more detail. The summary of mean results from the analysis of the fine fraction (<63 μm) is given in Table 5.15.

Core	CLA	CLB	CLC	CLD	CLE
Mean % less than 125 μm	93.1	82.4	88.3	89.0	88.8
Standard deviation	1.9	21.8	4.7	3.0	6.4
Mean % less than 63μm	47.1	37.8	51.7	45.45	46.9
Standard deviation	2.7	1.9	5.6	6.4	8.3

Table 5.14 Fine fraction characteristics for Caerlaverock (eroding site) cores

Core	CLA	CLB	CLC	CLD	CLE
Mean % less than 63 μm	64.7	77.1	66.3	65.6	67.4
Standard deviation	3.4	4.3	5.7	1.7	10.7
Mean % less than 32 μm	14.2	31.3	19.3	18.6	18.7
Standard deviation	3.4	5.4	7.7	5.6	9.1
Mean % less than 16 μm	7.1	16.4	10.2	9.7	9.4
Standard deviation	1.5	2.5	4.5	3.4	4.3
Mean % less than 7.8 μm	4.5	8.8	5.9	5.7	5.6
Standard deviation	0.7	1.0	2.2	1.7	2.3
Mean % less than 3.9 μm	2.9	4.6	3.4	3.4	3.5
Standard deviation	0.3	0.3	0.9	0.9	1.2

Table 5.15 Analysis of the fine fraction of Caerlaverock (eroding site) cores

Table 5.14 shows that only one core has more than 50 % of the sediment less than 63 μm and analysis from the Coulter 230LS shows that only one core has more than 70% of the sediment less than 63 μm. Interestingly, Core CLB shows the smallest percentage of sieved sediment less than 63 μm but the highest percentage less than 63 μm using the laser particle sizer. This suggests that because of the higher percentage of small particles they clumped together more, i.e. they formed agglomerates which could not pass through the sieve mesh. However, once treated with a dispersant, the percentage of fine particles could be determined with greater precision.

The core with the coarsest sediment is CLA located on the mudflat, whereas, the finest sediment is found in Core CLB, positioned on the terrace with the vegetation stripped away. The cores found within the rest of the marsh show remarkably similar results for all size fractions.

ACCRETING SITE

5.3.7 Geomorphology, vegetation and recent changes in the accreting study site

A map of the geomorphology of this site is shown in Map 3c and the vegetation and recent changes is shown in Map 3d. The site occupies an area of 3660 m^2. The study site is shown in Figure 5.8. There are four distinct geomorphological areas present on this part of the marsh: high marsh; low marsh; pioneer marsh and accreting mudflat.

5.3.7.1 High marsh

There is only a small area of high marsh included in the study site but it is readily identifiable because of its altitude and greater variety of vegetation species present. The vegetation comprises *Festuca, Puccinellia, Triglochin, Limonium* and *Aster.* Criss-crossing the surface of the marsh is a series of small creeks which are difficult to delineate because of the preponderance of vegetation. There is a small, vegetated cliff marking the edge of this part of the marsh, measuring around 15 cm.

It is clear that this part of the marsh has, in the past, experienced either erosion (resulting from, perhaps the migration of a tidal channel (Marshall, 1962)) or a period of non-continuous accretion (as a consequence of sea level rise (Hansom, 1988) . There are two pieces of evidence which point to this. Firstly, there is a cliff separating the high marsh from vegetated marsh lying seaward. If the marsh had gradually prograded without a period of erosion, there would be no cliff. Secondly, the isolated areas of the high marsh, separated from the main body of the marsh are likely to be related to erosion of the marsh.

5.3.7.2 Low marsh

The low marsh is situated seaward of the high marsh. The marsh is covered by a complete blanket of vegetation but the species present suggest the marsh has not been established for an extensive period of time. Only *Puccinellia* and *Ameria* are present, which are primary colonisers, *Puccinellia* being dominant. There are many small pans within this part of the marsh which are all devoid of vegetation. The circular form of the pans indicates that they are primary pans, probably created by the uneven nature of sediment deposition and plant colonisation, rather than elongate pan developed from the disruption of the creek network.

5.3.7.3 Pioneer marsh

The inception of pans can be identified on the pioneer marsh and the accreting mudflat. This area of the site is similar to that described above, but the vegetation cover is more sparse and the pan edges are less well defined. In addition there are a great many more 'pan areas'; that is bare areas of marsh sitting within vegetated areas. *Puccinellia* is the main vegetation species with *Ameria* present on only the highest parts of the pioneer marsh.

5.3.7.4 Accreting mudflat

The description of this area is difficult to define because it is scattered with small hummocks of primary vegetation and isolated patches of *Puccinellia*. On the highest parts of the hummocks may be found an isolated stand of *Ameria* vividly demonstrating the relationship between the height of marsh and vegetation type. It is in this area that the uneven nature of sedimentation can be fully appreciated. The hummocks with vegetation are higher than the surrounding bare areas and are actively trapping sediment (fresh sediment can be seen draped over the vegetation). The transition between the vegetated hummocks and the mudflat is usually gradual but there are some hummocks which have a small eroded edge (1 cm in height).

Due to the juvenile nature of the marsh, the level of inundation which occurs over a tidal cycle is significant, especially on the pioneer marsh and accreting mud. The high marsh is inundated only during high spring tides.

At the time the first map was drawn in 1995, there was a small creek meandering across the lower parts of the marsh, marking a boundary between the pioneer marsh and the accreting mud. The following year, 1996, however, part of the creek was gone, with only the deepest parts remaining. With this exception, there have been few other changes in the marsh. This is surprising given that it is new and actively advancing seawards. The height of some hummocks has increased, demonstrated by an increase in the amount of *Ameria* and the introduction of *Triglochin*. The positions of the pans and hummocks have shown no detectable change over the study period.

Plate 5.6 illustrates the progression from the pioneer marsh to the mudflat .

Plate 5.6 Accreting site at Caerlaverock Merse illustrating the gradual change from pioneer marsh to unvegetated mudflat.

5.3.8 Sedimentation in the accreting study area

The location of the plates used to establish the sedimentation pattern and rates across the study sites are shown in Map 3c. The calculated rates (cm y^{-1}) are given in Appendix 3, Table (vi), with a summary in Table 5.16. No plates were lost by erosion on this site although some were only relocated with the use of a metal detector because the location marker pegs used were either covered with sediment or were washed away. The range of sedimentation rates is from 1.3 cm y^{-1} to 4.0 cm y^{-1}.

Plate	Position on marsh	Accretion Rate (cm y^{-1})
1	Low marsh	1.5
2	Low marsh	1.9
3	High marsh	1.3
4	High marsh	1.3
5	Low marsh	2.0
6	Pan	*
7	High marsh	1.9
8	Low marsh	2.0
9	Low marsh	2.3
10	Pioneer marsh	*
11	Pioneer marsh	2.6
12	Pioneer marsh	1.7
13	Accreting mud	2.0
14	Accreting mud	2.0
15	Mudflat	4.0
16	Mudflat	1.7
17	Mudflat	3.2
18	Pioneer marsh	*
19	Pioneer marsh	2.8
20	Pioneer marsh	2.5
21	Pioneer marsh	2.6
22	Bare mud	*
23	Pioneer marsh	2.8
24	Pioneer marsh	2.2
25	Accreting mud	3.7
26	Mudflat	*
27	Mudflat	3.3
28	Mudflat	3.7
* unable to calculate		

Table 5.16 Summary of Caerlaverock (accreting site) plate results

Plates 3 and 4. located on the highest part of the marsh indicated the lowest sedimentation rates, both being 1.3 cm y^{-1}. Plates 1 and 2, located on the low marsh gave rates of 1.5 cm y^{-1} and 1.9 cm y^{-1}. These four plates are the furthermost inland within the study site. Plate 8 is 20 m south of Plate 4 and has a higher rate of 2.0 cm y^{-1}. From these results it appears that the high marsh and the low marsh furthest inland are all accreting at similar rates.

The locations with the plates located on the pioneer marsh, Plates 11, 12, 19, 20, 21, 23 and 24, are accreting at a slightly higher rate, 2.6 cm y^{-1}, 1.7 cm y^{-1}, 2.8 cm y^{-1}, 2.5 cm y^{-1}, 2.6 cm y^{-1}, 2.8 cm y^{-1} and 2.2 cm y^{-1}. The slightly lower rate of Plate 24 may perhaps be attributed to the fact that it is next to an ephemeral creek resulting in decreased sedimentation in areas around the creek.

The highest sedimentation rates are shown at Plates 15, 25, 27 and 28 with rates of 4.0 cm y^{-1}, 3.7 cm y^{-1} and 3.7 cm y^{-1}. These plates are located either on mudflat or pioneering marsh.

The remaining plates are all located on the mudflat and all indicated very similar accretion rates. These are Plates 16, 17, 27 and 28 and have rates of 3.4 cm y^{-1}, 3.8 cm y^{-1}, 3.6 cm y^{-1} and 3.5 cm y^{-1}.

These results show that areas which are frequently inundated by the tide, that is the mudflats and the accreting mud, have the highest sedimentation rates. Within these sections, areas which are vegetated, even if only slightly, have higher accretion rates. As the amount of tidal inundation decreases towards the landward areas of the marsh, the accretion rates reduce.

5.3.9 Determination of organic content of sediment within the accreting marsh sediments

The location of the cores used for analysis of sediment organic content and radionuclide concentration is shown in Map 3c and described in Table 5.17. The results of the analysis for organic content, given as the percentage Loss on Ignition are presented in Appendix 3, Table (vii) and summarised in Table 5.18. Graphs of each core profile are illustrated in Figure 5.11. The % LOI values across the whole site range from 0.4 % to 6.59 %.

Core	Location
CKA	Mudflat
CKB	Mudflat
CKC	Pioneer marsh - *Puccinellia*
CKD	Low marsh - primary and secondary vegetation present
CKE	Low marsh - primary and secondary vegetation present
CKF	Low marsh - primary and secondary vegetation present
CKG	Accreting mud, next to area of pioneer marsh
CKH	Pioneer marsh - *Puccinellia*
CKJ	High marsh
CKK	High marsh - 10m inland from CKJ

Table 5.17 Core locations on Caerlaverock accreting site

Core	% LOI	
	Range	Mean and standard deviation
CKA	1.6 - 3.7	1.9 +/- 0.29
CKB	1.0 - 2.6	1.6 +/- 0.4
CKC	1.5 - 0.5	1.5 +/- 0.48
CKD	31.4- 2.8	1.6 +/- 0.44
CKE	1.0 - 3.6	2.0 +/- 0.51
CKF	0.8 - 6.6	2.0 +/- 1.19
CKG	1.0 - 2.6	1.7 +/- 0.35
CKH	1.0 - 3.0	1.8 +/- 0.58
CKJ	1.2 - 5.0	2.3 +/- 0.93
CKK	0.4 - 4.4	2.1 +/- 0.95

Table 5.18 % LOI summary statistics for Caerlaverock accreting site

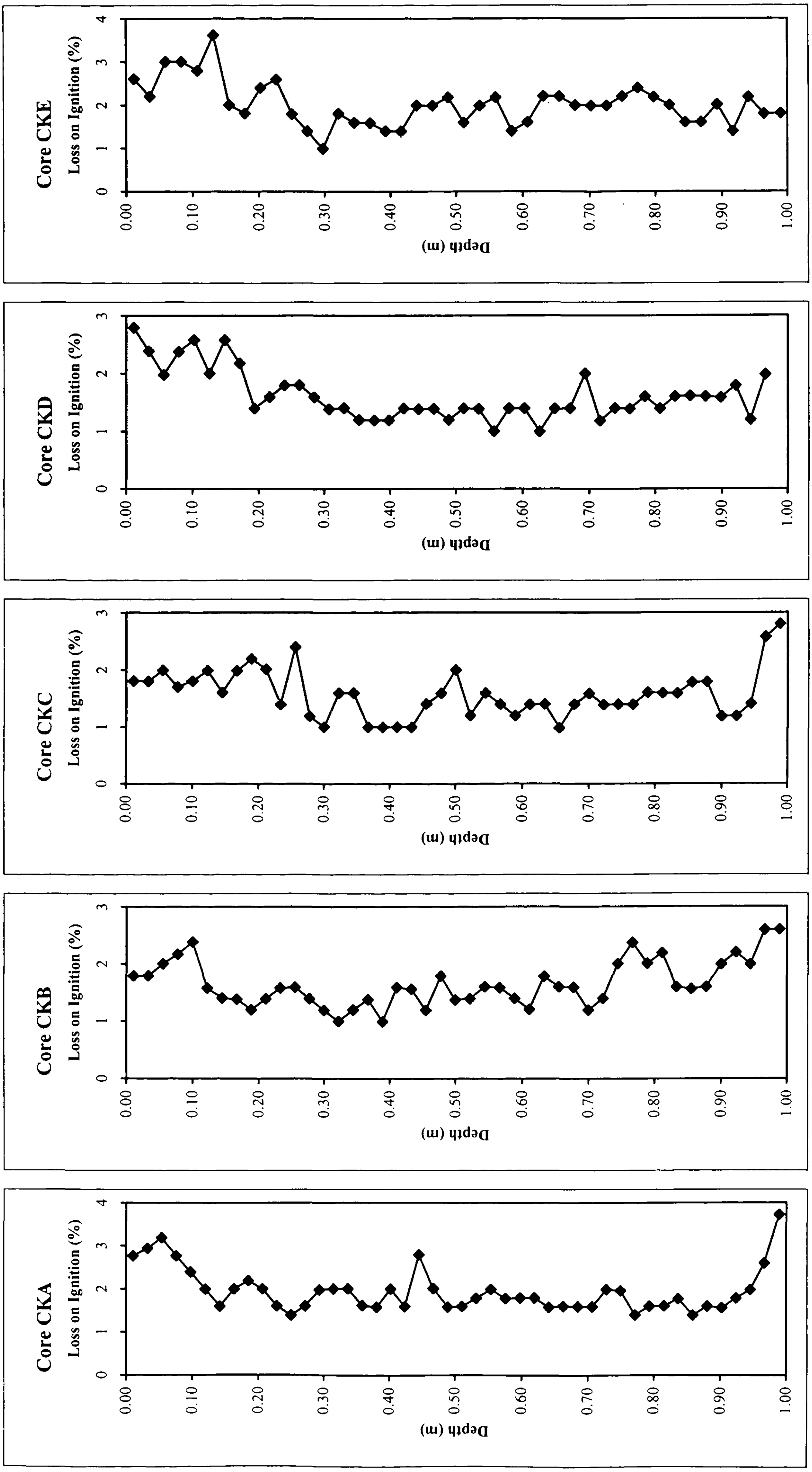


Figure 5.11 Percentage Loss on Ignition - Cores CKA, CKB, CKC, CKD, CKE

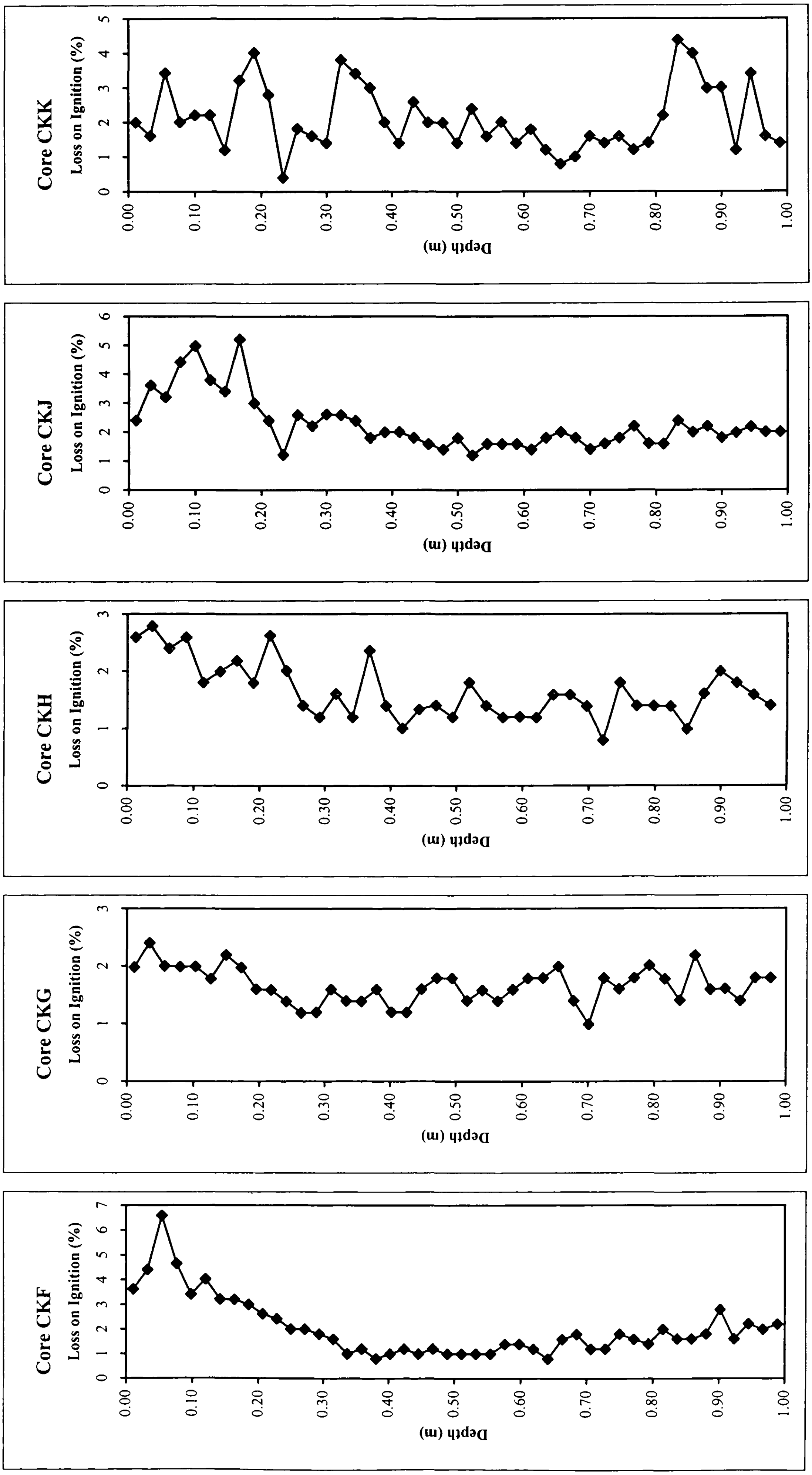


Figure 5.11 (cont.) Percentage Loss on Ignition - Cores CKF, CKG, CKH, CKJ, CKK

Core CKA is located on the mudflat, some 25 m from any colonising vegetation. The organic content of the core is highest at the top and bottom of the core. Between the depth of 25 cm and 86 cm the organic content does not vary greatly. There is a small peak at 45cm.

Core CKB is also located on the mudflat and is only 5 m from the beginning of vegetated areas. The pattern of organic content shown in the core is similar to that of Core CKA in that the highest values are found at the top and bottom of the core. The values at the top increase to a peak at 10 cm and then reduce slightly to a depth of 30 cm. From this point the values are variable down the core although the trend is a gradual increase towards the base of the core.

For core CKC, located in an area of primary vegetation, the % LOI reduces gradually from the top of the core to a depth of 30cm, although superimposed on this trend are a number of peaks and troughs. Below 30 cm, there is a slight increase in values towards the base. There are small peaks at depths of 26 cm, 50 cm and at the base of the core.

Core CKD is on low marsh. The top of the core, to a depth of 19cm, has the highest organic content in the whole core. As with the other cores, the higher % LOI values at the top reduce to a depth of around 30 cm. From this point however the organic content increases slightly towards the base of the core but does not exceed the levels found at the top.

Core CKE is also located on the low marsh and is similar to CKD in that the highest values are found at the top of the core. The values generally reduce to a depth of 30 cm, although there are peaks at 13 and 23 cm. From this point there is again a general increase towards the base of the core.

Core CKF, located 20 m inland from Core CKE, is still on low marsh but the profile of organic content is much more dramatic. The highest organic content is found at the top of the core. The organic content peaks at 5 cm and gradually reduces to a minimum at 45 cm. There is then, as with the other cores, a gradual increase in organic content towards the base of the core.

Core CKG is located on the accreting mud, near some pioneer vegetation. The organic profile is very similar in appearance to that of Core CKB which is in a similar location. The organic content is slightly higher at the top and values reduce to around 30 cm. There is a slight increase towards the core bottom.

Core CKH, located on the low marsh has a similar to the profile to that of Core CKD, in that the organic content is higher at the top of the core than at depth. The organic content reduces from the top to a depth of around 30 cm. Below this, there is perhaps a slight increase to the base of the core although this is difficult to establish because of a number of peaks and troughs masking the general trend.

Core CKJ is located on the high marsh. The highest organic content is again within the top 23 cm of the core, although there is some variation within this top part with peak values occurring at depths of 10 cm and 17 cm. From a minimum value at 23 cm depth, the organic content increases slightly towards the base of the core.

Core CKK is located within the high marsh, 10 m inland from CKJ. The profile of this core is very different to any of those already described for this marsh. There are a number of organic peaks in organic matter content down the profile, the most significant occurring at depths of 6 cm, 19 cm, 32 cm, 83 cm and 94 cm. No general pattern can be discerned from these results, except that there is a lot of variation.

In summary, the extent of variation in the organic content within the cores increases with marsh maturity. Core CKK, excavated from the mature marsh, exhibits variation down the length of the core profile. In most cases the highest organic contents are towards the surface of the cores corresponding with the establishment of vegetation. Cores CKF and CKJ, display very high organic contents near the surface illustrating a more mature vegetation assemblage. Cores excavated from the mudflat and pioneer marsh have the lowest organic content.

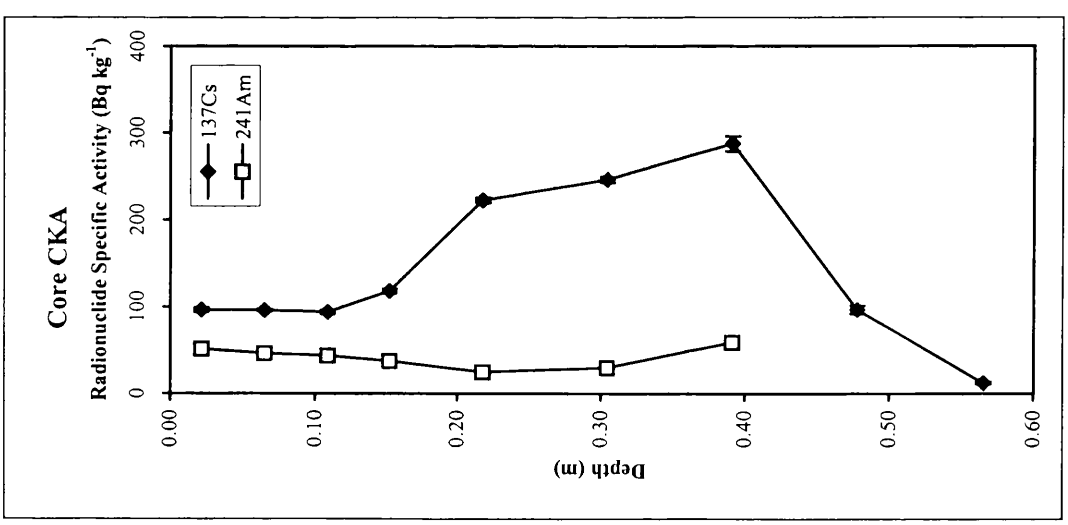
5.3.10 Radionuclide concentrations across the accreting study area

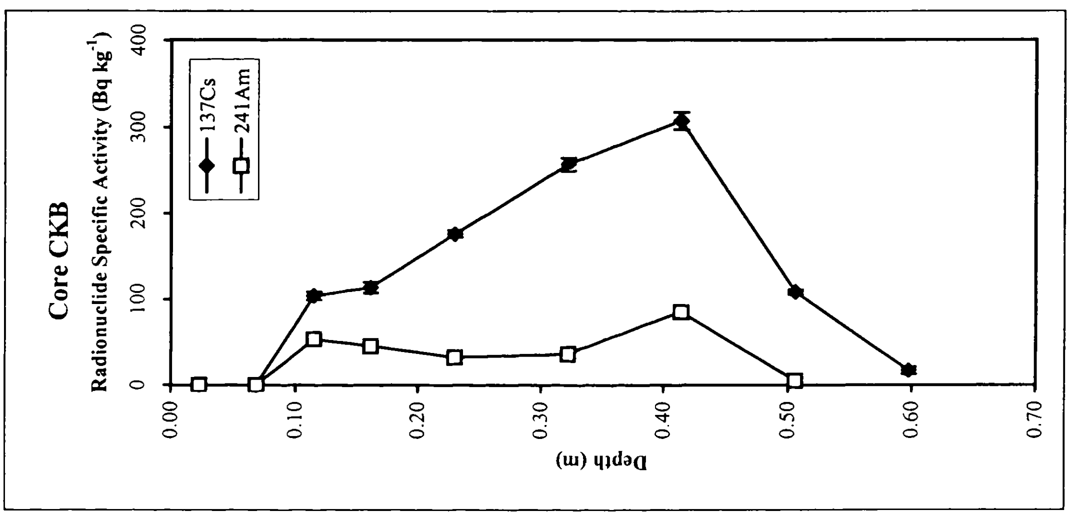
Of the cores described in Table 5.17, six were analysed for radionuclide concentrations, in order to assess the variability in contamination with distance inland, varying saltmarsh types and at depth in the saltmarsh. The five cores, CKA, CKB, CKC, CKD, CKE and CKF, represent a transect from the mudflat to the high marsh. The analysis of the cores was treated in the same manner as for the eroding part of Caerlaverock (Section 5.3.6).

The results for those cores are given in Appendix 3, Table (viii). The profiles are illustrated in Figure 5.12. As with those excavated from Orchardton and the eroding part of Caerlaverock, the cores from this site do not exhibit detectable levels of either ^{137}Cs or ^{241}Am down the full length of the core. The range of radionuclide specific activities is from 5 Bq kg^{-1} to 442 Bq kg^{-1} for ^{137}Cs and 5 Bq kg^{-1} to 124 Bq kg^{-1} for ^{241}Am.

The ^{137}Cs and ^{241}Am profiles illustrated for Core CKA are markedly different to cores which have been analysed thus far, in that the patterns for the two radionuclides are very different. Core CKA has a ^{137}Cs specific activity ranging from 12 Bq kg^{-1} to 288 Bq kg^{-1} while ^{241}Am ranges from 25 Bq kg^{-1} to 60 Bq kg^{-1}. The ^{241}Am profile is featureless with the activity changing little with depth. The ^{137}Cs profile on the other hand demonstrates the sub-surface maximum evident on other marshes. The peak activities are found at a depth of around 39 cm. The $^{137}Cs/^{241}Am$ activity ratio ranges from 1.9 to 9.1. The highest values are associated with the peak in ^{137}Cs activity.

Core CKB is located in the same mudflat environment as CKA and displays a very similar set of radionuclide profiles with the exception that CKB has very low ^{137}Cs and ^{241}Am activities at the top of the core, with both being below detectable limits. The ^{241}Am activities range from 5 Bq kg^{-1} to 85 Bq kg^{-1} with a small peak evident at 41 cm. The range of ^{137}Cs activities is from 17 Bq kg^{-1} to 307 Bq kg^{-1}. There is a peak in ^{137}Cs at a depth of around 41 cm, similar to the peak in Core CKB (given that the depth indicated on the profile reflects the average depth as a consequence of sampling strategy used for Caerlaverock). The $^{137}Cs/^{241}Am$ activity ratio ranges from 2 to 7.1. There is a value of 22 at the base of the core, reflecting the very low ^{241}Am concentration. The peak ratio is roughly coincident with the highest ^{137}Cs activities.





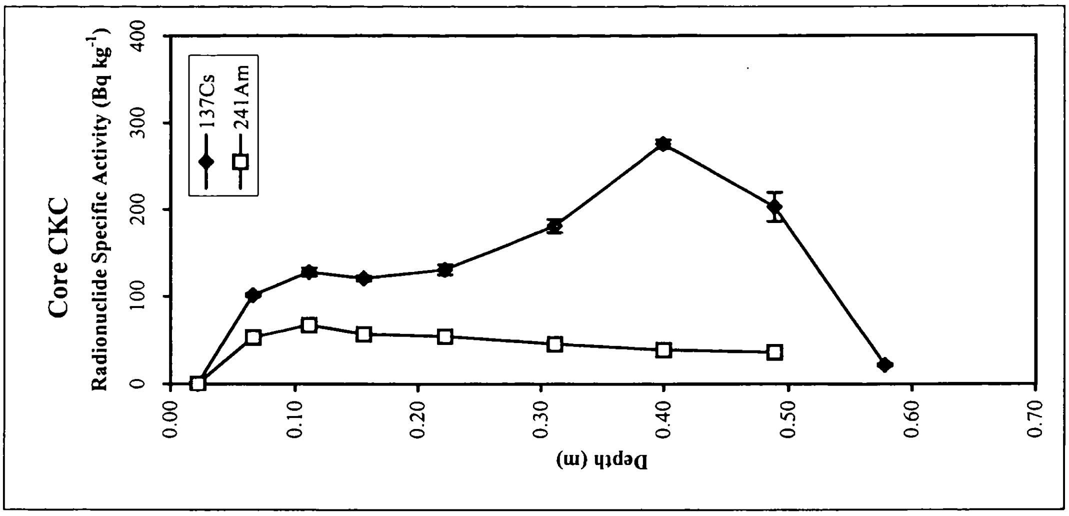


Figure 5.12 Radionuclide specific activity profiles - Cores CKA, CKB, CKC

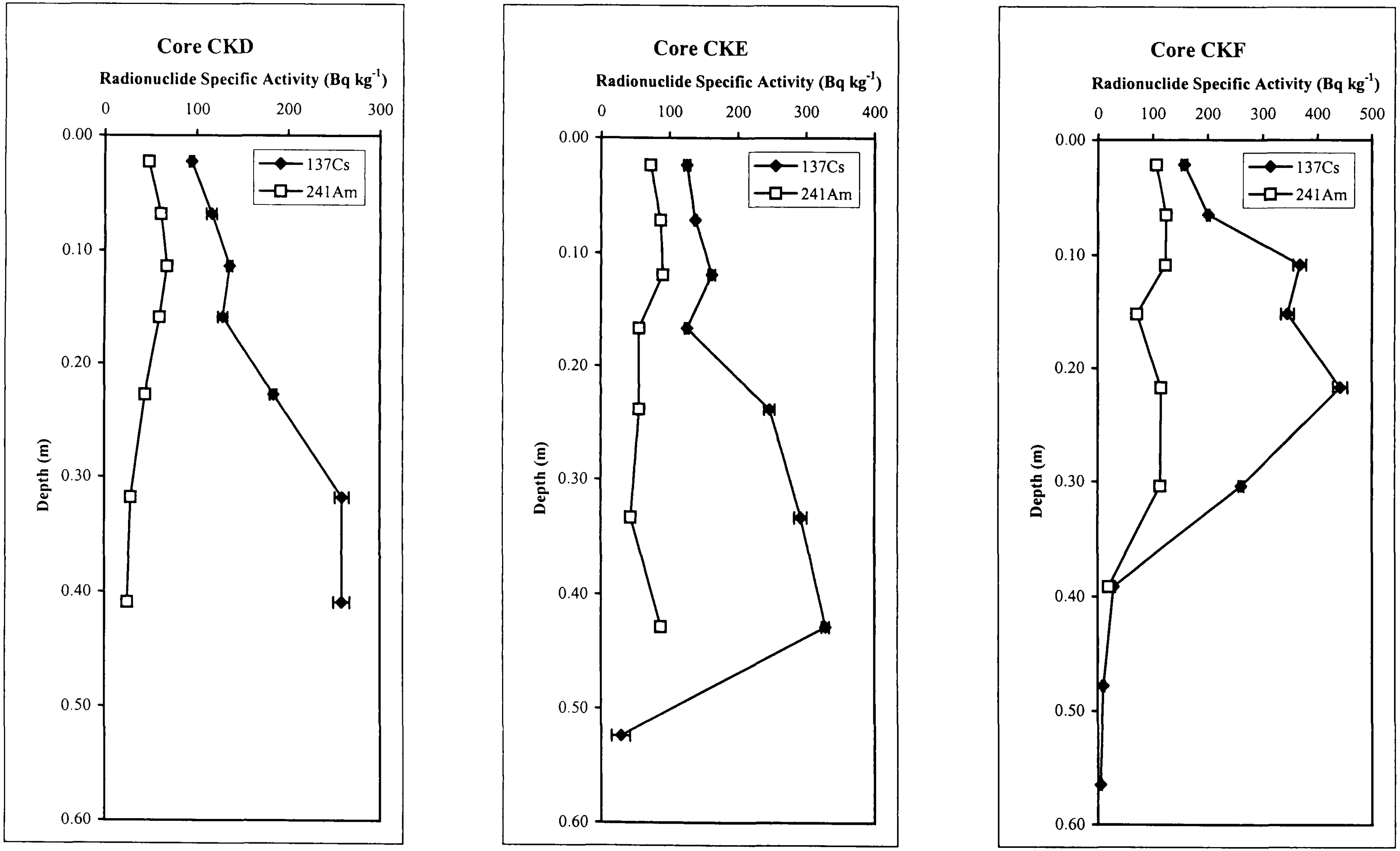


Figure 5.12 (cont.) Radionuclide specific activity profiles - Cores CKD, CKE, CKF

Core CKC is located in an area of pioneer *Puccinellia.* The concentrations of both ^{137}Cs and ^{241}Am are below detection limits at the top of the core but increase above this at a depth a depth of 7 cm. ^{137}Cs specific activities range from 22 Bq kg^{-1} to 276 Bq kg^{-1}. The ^{137}Cs concentrations again illustrate a sub-surface maximum at a depth of 40cm. The ^{241}Am activities range from 36 Bq kg^{-1} to 67 Bq kg^{-1}, the highest values being found towards the top of the core with no peak found at depth. The $^{137}Cs/^{241}Am$ activity ratio ranges from 1.9 to 7.1. The peak ratio is found at the same depth as the peak ^{137}Cs activities.

Core CKD, located on the low marsh has ^{137}Cs specific activities ranging from 94 Bq kg^{-1} to 259 Bq kg^{-1} and ^{241}Am from 25 Bq kg^{-1} to 67 Bq kg^{-1}. The ^{241}Am profile shows a slight increase towards the top of the core but there is no definable peak. The ^{137}Cs activities peak at a depth of 41 cm. The $^{137}Cs/^{241}Am$ activity ratio increases steadily towards this depth.

In Core CKE, again located within the low marsh, the ^{241}Am profile has a weak sub-surface peak although it is not as defined as either the ^{137}Cs peaks in this marsh or ^{241}Am peaks exhibited in other marshes. The ^{241}Am activity ranges from 44 Bq kg^{-1} to 91 Bq kg^{-1} with the peak value at a depth of 12 cm. Coincident with this increase in ^{241}Am concentrations is a slight increase in ^{137}Cs activities , resulting in the $^{137}Cs/^{241}Am$ ratio remaining below 2. Below this depth however, the ^{137}Cs activity increases three fold to a maximum value of 329 Bq kg^{-1} at a depth of 43 cm. The $^{137}Cs/^{241}Am$ activity ratio increases to a maximum of 6.6 at a depth of 33 cm. The ratio reduces slightly at 43 cm because of a slight increase in ^{241}Am concentrations.

Core CKF, the most inland core of this sequence, demonstrates similar, but more pronounced, patterns to those in Core CKE. The ^{137}Cs specific activity ranges from 5 Bq kg^{-1} to 442 Bq kg^{-1} with peak values at depths of 11 cm and 22 cm. The ^{241}Am specific activity ranges from 19 Bq kg^{-1} to 124 Bq kg^{-1} with a peak at 11 cm. The $^{137}Cs/^{241}Am$

activity ratio is below 2 at the top of the core but increases to 4.9 at 15 cm depth. It then decreases again to 40 cm, where both radionuclides reduce to very low levels.

The three cores located on the mudflat and pioneer marsh, CKA, CKB, CKC, have remarkably similar profiles for both ^{137}Cs and ^{241}Am. The ^{241}Am profiles are generally featureless whereas the ^{137}Cs profile exhibits a subsurface maximum at a depth of around 40 cm. The ^{241}Am values are all below 90 Bq kg^{-1}. The ^{137}Cs peak values within these three cores are also very similar, ranging between 276 Bq kg^{-1} ($\pm$ 5 Bq kg^{-1}) to 307 Bq kg^{-1} ($\pm$ 10 Bq kg^{-1}). In Cores CKD, CKE and CKF the ^{241}Am profile demonstrates a small peak at a depth of 12 cm. ^{137}Cs activities also rise at this point. There is still a sub-surface maximum in the ^{137}Cs profile with activities reaching their highest levels in the most inland cores. The ^{137}Cs peak in Core CKF is at a shallower depth than in any of the other cores on this site.

5.3.11 Analysis of sediment sizes within cores from the accreting marsh

Samples from each of the cores analysed for radionuclides were sieved and analysed using the Coulter 230LS laser particle sizer. The results, expressed as the percentage coarser then the sieve size are given in Appendix 3, Table (ix). The results from the Coulter 230LS analysis are expressed as the percentage of sample finer than a particular size and are given in Appendix 3, Table (x).

Analysis of the sieving results from all the cores shows that 94.9 % (standard deviation 2.1 %) of sediment is less than 125 μm and that 39.9 % (standard deviation 5.2 %) is less that 63 μm demonstrating, once again the fine nature of these saltmarsh sediments. Table 5.19 illustrates this in more detail. The summary of mean results from the analysis of the fine fraction (<63 μm) is given in Table 5.20.

Core	CKA	CKB	CKC	CKD	CKE	CKF
Mean % less than 125 µm	94.2	96.3	97	95.9	94.7	91.2
Standard deviation	1.4	0.8	1.4	2.0	1.7	3.9
Mean % less than 63µm	35	35.3	40	36.6	45.6	46.8
Standard deviation	14	8	12.6	6.2	11.5	8.1

Table 5.19 Fine fraction characteristics for Caerlaverock (accreting site) cores

Core	CKA	CKB	CKC	CKD	CKE	CKF
Mean % less than 63µm	54.7	53.4	55.8	59.7	61.9	65.6
Standard deviation	2.2	2.4	3.5	3.0	4.8	4.7
Mean % less than 32µm	8.0	8.0	8.5	11.1	12.4	16.3
Standard deviation	0.8	1.5	1.5	2.6	3.7	2.3
Mean % less than 16µm	4.4	4.6	6.6	5.7	6.3	8.4
Standard deviation	0.5	1.0	2.3	1.3	1.6	0.6
Mean % less than 7.8µm	3.2	3.3	3.4	3.7	4.0	5.08
Standard deviation	0.2	0.6	0.4	0.5	0.7	0.2
Mean % less than 3.9µm	2.4	2.4	2.5	2.5	2.7	3.2
Standard deviation	0.1	0.3	0.2	0.1	0.3	0.1

Table 5.20 Analysis of the fine fraction of Caerlaverock (accreting site) cores

The summary results for the analysed cores are very similar for each size fraction, especially in Cores CKA, CKB and CKC. For example the mean percentage less than 63 µm for these cores is 55 %, 54 %, and 56 % respectively: the amount of clay in these cores is 2.4 %, 2.4 % and 2.5 %. The two cores which are the further inland, CKE and CKF have higher percentages of fine sediment than three cores just mentioned. The clay values for CKE and CKF cores are 2.7% and 3.2% respectively. It can therefore be concluded that the mudflat and pioneer marsh have slightly coarser sediment than marsh which has more established vegetation.

5.4 Site comparisons

In the following section, some very brief comparisons of the data for each site will be made. This is not intended to be a discussion of the data but simply an articulation some of the main trends and differences between the sites which will be considered in more detail in following chapters.

5.4.1 Sedimentation patterns and rates

All four sites have large variations in sedimentation rates across different areas of the marsh. In Southwick, the highest sedimentation rates occurred towards the front of the marsh and near creeks. This pattern was also evident at both the eroding and accreting sites at Caerlaverock, although the rates at Southwick are higher than those on Caerlaverock. The lowest sedimentation rates on Southwick were found at the most landward localities and again this pattern was replicated on both Caerlaverock sites, although the highest rates measured in these high marsh areas were, this time, found on the eroding site at Caerlaverock. The patterns shown at Southwick and Caerlaverock were not evident at Orchardton, where there was very little active accretion on the vegetated saltmarsh.

On all marshes, the mudflat areas, fronting the marsh were subject to high levels of sedimentation, although proximity to tidal channels resulted in some erosion on Southwick and Orchardton mudflats. The highest sedimentation rates on mudflat areas were found at the eroding site of Caerlaverock.

Only two of the sites, Orchardton and the eroding site at Caerlaverock experienced appreciable erosion. At Orchardton erosion occurred across the whole marsh surface, whereas at Caerlaverock the erosion was concentrated at the front of the marsh by the retreat of two cliffs.

5.4.2 Comparison of organic data between sites

The cores on Southwick, especially those found on more mature areas of marsh exhibited large variations in % LOI. Similar variation was also shown in cores from

Orchardton, specifically, ORH, ORJ and ORK, and the accreting site at Caerlaverock, Core CKK. Overall, however, variation shown in the profiles of the Southwick cores is greater than that at the other sites. It was suggested that the % LOI pattern shown in the Southwick cores depicted a sedimentation regime in which vegetation growth on the saltmarsh was buried by sediment producing layers of organic rich and organic poor sediment. The differences in the core profiles between Southwick and the other sites suggest that the method of sedimentation between the sites differs. This difference is most apparent on the Orchardton sites which have low amounts of *Spartina* vegetation colonising the marsh, and on the pioneer marsh areas on the accreting Caerlaverock site.

The majority of cores on the eroding site at Caerlaverock show very different organic profiles to those on other sites. The cores excavated from the vegetated marsh all have a sub-surface maximum in organic values found at depth, with the depth of the peak depending on the degree of inundation experienced in that part of the marsh.

On all the sites, organic values measured in cores excavated from mudflat areas are low, generally being less than 4 %, and often less than 3 %. The highest values were observed in the sub-surface peaks on the eroding Caerlaverock site. Comparison of high marsh areas in the four sites shows Orchardton to have the highest organic content down the length of the cores, although Southwick and the accreting Caerlaverock site have high organic values at the top of high marsh cores.

5.4.3 Radionuclide specific activities and activity ratios

The comparison of radionuclide activities is complicated by the slightly different sampling strategies in later sites. Despite this, however, the profiles are comparable, especially for Southwick and Orchardton which have the most data available. While the Caerlaverock cores were analysed at a much coarser sampling interval, the profiles are still informative and reveal significant differences between Caerlaverock and the other two sites.

On Southwick, Orchardton and the eroding site at Caerlaverock, the cores excavated from mudflats all have unremarkable radionuclide activity profiles. The ^{137}Cs and ^{241}Am

values are similar resulting in $^{137}Cs/^{241}Am$ ratios of around 1. With the exception of the mudflat sites, all other cores have higher activities of ^{137}Cs than to ^{241}Am.

Cores excavated from vegetated marsh all exhibit a subsurface maximum for ^{137}Cs and ^{241}Am, although in the accreting Caerlaverock site, the ^{241}Am peak is insignificant. In general, the depth at which the peak occurs in the core depends on the amount of tidal inundation experienced. Those areas which have a higher hydroperiod, exhibit the radionuclide peak at lower depths.

The depth over which the peak radionuclide activities occur, differs in each of the sites. At Southwick, the cores which have pronounced peaks, SWG, SWH, SWJ, and SWK, have the peaks occupying a depth increment of at least 30 cm. At Orchardton, the depth occupied by the peak is less, even taking into account the modified sampling procedure. This is also the case at the eroding Caerlaverock site. At the accreting Caerlaverock site, the peak extends over a distance of 30cm or more in all cores. It should however be noted that in these cores, only the ^{137}Cs peak is pronounced.

The concentrations found in the cores across the four sites also varies. It has already been shown that mudflat sediments have roughly similar ^{137}Cs and ^{241}Am specific activities across the four sites. The highest activities are found at Orchardton in those cores occupying vegetated marsh locations, although those at Southwick are only slightly lower. The lowest activities are found at Caerlaverock.

Comparisons can also be made between the $^{137}Cs/^{241}Am$ activity ratios for the different sites. At Southwick, Orchardton and the eroding Caerlaverock site, the lowest ratios are associated with the mudflat cores, where the ratios rarely exceed 2. The highest ratios on all sites are found coincident with the subsurface maxima because of elevated ^{137}Cs concentrations. Again at Southwick, Orchardton and the eroding Caerlaverock site, the ratios associated with peak radionuclide concentrations are around 2.5. At the accreting Caerlaverock site however, the ratio is as high as 9.

5.4.4 Sediment size analysis

The analysis of sediment size in all sites shows that the sediments constructing the saltmarshes are very fine grained. The sieving results show that at least 75% of sediment is below 125 μm. Sieving also shows that Orchardton has the highest percentage of sediment less than 63 μm with Southwick having the second highest. The accreting Caerlaverock site has slightly coarser sediment present than the eroding site. The laser particle sizer shows that Caerlaverock has the smallest amount of clay size particles in the sediment.

All sites show that the finest sediment is found in parts of the marsh which are inundated least by tidal water. These areas are generally the furthermost inland areas. Both Southwick and Orchardton have between 6 % and 7 % clay in high marsh areas. At the Caerlaverock sites values for equivalent sites are reduced to between 3 % and 4 %. The mudflat areas have reduced amounts of clay although even in this respect, Southwick has a higher percentage of clay particles.

6 ANALYSIS AND DISCUSSION OF STUDY SITES

6.1 Introduction

The results presented in Chapter 5 intimate that significant differences exist between the study sites in terms of their geomorphology, sedimentology and radionuclide content. The principal aim of this thesis is to evaluate the role of geomorphological processes in the distribution and fate of contaminant radionuclides within Solway saltmarshes and to identify processes which influence future trends in radionuclide concentrations and distributions. This overall aim is addressed in the following analysis, in addition to several specific objectives outlined as follows:

- investigate the influence of physiographic location on saltmarsh development;
- to integrate the use of different investigative methods over different timescales, to establish sedimentation rates and patterns in the Solway saltmarshes, and to identify the geomorphological factors responsible for these rates and patterns, in the context of varying vegetation species;
- to determine the influence of physical conditions on a saltmarsh (tidal influence, vegetation, sediment size, organic content) in understanding radionuclide patterns and concentrations;
- to use the pattern of radionuclide concentrations as a tool to investigate saltmarsh development processes;
- to explore the extent to which post depositional mixing of sediment, as a result of physical processes, affects the subsequent distribution and concentration of ^{137}Cs and ^{241}Am in a saltmarsh system.

The interpretation of results is presented in the next two chapters: Chapter Six constituting an intra-marsh discussion related to variations within individual sites and Chapter Seven an inter-marsh discussion examining patterns between saltmarshes.

6.2 Southwick

6.2.1 Sedimentation rates and patterns derived from plate results

Saltmarsh sedimentation patterns identified in the literature show that in general, the highest rates of sedimentation occur at the seaward end of a marsh, reducing inland with height and marsh maturity (Letzsch and Frey, 1980; Pethick, 1981; Gray, 1992). More specifically, higher rates of sedimentation occur close to creeks which channel tides into and out of the marsh (e.g. Letzsch and Frey, 1980; Oenema and DeLaune, 1988; Stoddart *et al.*, 1989). It is argued that, on a short time scale, sedimentation rates are controlled by proximity to creeks while on a longer time scale, elevation is the more important factor. French and Spencer (1993) indicate that tidal overflow of the seaward edge of the marsh is also a contributor to sedimentation patterns. In macro-tidal systems, the dominant control mechanism for sediment deposition, can be attributed to sediment settling from tidal water, with the resultant sedimentation pattern being modified by settling and scour lag processes and the duration and depth of slackwater (Letzsch and Frey, 1980; Reed and Cahoon, 1992; Cahoon and Reed, 1995). In addition, the extent and type of marsh vegetation present is important, and, in some instances, may be more important, than direct settling (Stumpf, 1983). Sedimentation via storm activity is also considered important in both micro- and macro- tidal environments. In the latter, storm activity often with a seasonal component may be responsible for long term sedimentation on the highest marsh surfaces (French and Spencer, 1993).

Sedimentation patterns at Southwick saltmarsh conform with observations reported in the literature. Mudflat sedimentation rates are hugely variable, with two plates exhibiting net accretion rates of 2.1 and 2.3 cm y^{-1} (Plates 23 and 25) and another (Plate 24) giving an erosion rate of -5.3 cm y^{-1}. However, such net sedimentation rates obscure individual periods of erosion and accretion. Although Plate 23 has an overall accretion rate of 2.1 cm y^{-1}, the net accretion over 9 months was 9.5 cm y^{-1} declining to 3.9 cm y^{-1} over 22 months, illustrating that the mudflat has been subject to a reduced sedimentation rate or even erosion between the two measurements. The accretion rate presented for Plate 25 masks an erosional event that resulted in the plate being washed away before the final set of measurements were taken, again illustrating the variable nature of the mudflat processes. Erosion at the location of Plate 24 was caused by the migration of a small mudflat creek situated 2 m from the plate at the time of plate insertion.

The mudflat is subject to extensive flooding and so represents a sedimentary regime which although predominantly accretionary, is subject to variability. The meandering of small tidal creeks and remobilization of sediment over a short time period is commonplace and results in the surface sediment being subject to mixing processes, a conclusion which will be explored further. Such a highly mobile mudflat system is expected for two reasons. Pye and French (1993) note that as sediment consolidates under its own weight, inter-particle cohesion, bulk density and shear strength are increased, thereby increasing resistance to erosion and resuspension. However, recently deposited mudflat sediment is subject to resuspension before consolidation occurs because it is unlikely to become dry between tidal inundations (Hutchinson *et al.*, 1995). Further, on the mudflat there is no vegetation and thus little decayed organic input to sediments protecting the surface from reworking and erosion (Evans, 1965; Ingram *et al.,* 1980). The mudflat surface at Southwick has a lower organic content than the vegetated saltmarsh, and this function of vegetation, Allen (1992b) argues, has not been fully assessed.

Saltmarsh sedimentation patterns can be explained with reference to the maturity of the marsh, the pattern of tidal inundation and proximity to creeks. Sedimentation rates vary with location on the marsh. For example, the sedimentation plates at Southwick show that as the front edge of the marsh is approached, the accretion rate increases. Four plates, 2, 6, 17 and 21, located from the high marsh, progressively closer to the front of the marsh, illustrate this pattern, with rates of 1.3 cm y^{-1}, 1.6 cm y^{-1}, 2.8 cm y^{-1} and 5.1 cm y^{-1}, respectively. This pattern is confirmed with reference to Plates 5b and 11 (70 m and 30 m from the marsh edge, respectively) and Plates 7 and 14 (50 m and 30 m from the marsh edge). The pattern is also confirmed by a series of plates lying in close proximity to a small creek. Plates 4 and 5a, located on opposing banks of a small creek, have rates of 1.9 cm y^{-1} and 2.1 cm y^{-1} while Plates 8 and 9, located seawards on the same creek, have rates of 2.7 cm y^{-1} and 2.6 cm y^{-1}. These results support the view that as marsh height, and therefore maturity, increases inland, the rate of sedimentation reduces because of reduced frequency of tidal inundation and depth of slackwater, limiting sediment supply (e.g. French, 1993, Carter, 1988).

The pattern, however, also has internal variability. Consider Plates 11 and 14 which are both located in the middle marsh 30 m from the marsh edge, and have sedimentation rates of 2.6 cm y^{-1} and 4.6 cm y^{-1} respectively. Their different rates can be attributed to both their location on the marsh and the manner in which they are inundated. Plate 14 lies at a lower position and is inundated by the main tidal channel, Southwick Water, while Plate 11 is supplied with flood water from a smaller creek within the marsh. Plate 14 experiences increased inundation but also, the greater scale of Southwick Water, in terms of both volume of water and sediment supply, means that those parts of the marsh inundated directly from this source will experience greater sedimentation.

The influence of Southwick Water is reflected in many of the sedimentation rates gathered from the site. For example, Plate 1 sits in the high marsh at 10 m equidistant from two creeks. Although flooded infrequently, this part of the marsh is subject to inundation directly from Southwick Water. Plate 2, also on the high marsh, is 6m from the nearest creek but not flooded by Southwick Water. The influence of Southwick Water is reflected in a higher sedimentation rate at Plate 1 than Plate 2 (2.2 cm y^{-1} and 1.3 cm y^{-1} respectively). Similarly, Plate 3, which is inundated by Southwick Water, can be compared with Plates 5b and 6, which are not (2.9 cm y^{-1}, 2.0 cm y^{-1} and 1.6 cm y^{-1} respectively).

In addition to the influence of Southwick Water and proximity to the marsh front, the sedimentation pattern is also affected by tidal flows and the planform of creeks within the marsh. Plates 4 and 5a are located on opposite banks of a creek which is relatively straight and therefore each bank is subject to approximately the same water velocities and inundation. Consequently, the plates have similar accretion rates. This pattern is similarly demonstrated by Plates 8 and 9. Plates 15 and 16, however, are located on opposite banks of a meander in a large creek. Plate 15, on the inner part of the meander has a rate of 6.3 cm y^{-1}, whereas Plate 16 is on the outer bend has a rate of 2.1 cm y^{-1} and is probably a reflection of a lower tidal velocity flowing around the inner bank of the meander and enhanced sediment deposition. Indeed, Plate 18 located on the inner bank of the largest creek rapidly became deeply buried and its location became difficult to establish after the first measurement.

Several studies suggest that sedimentation rates decline with increasing distance from creeks (e.g. Stumpf, 1983; Allen, 1992b), however, there is little such evidence at Southwick. Plates 4 and 5a, located on either side of a small creek, exhibit very similar sedimentation rates to Plate 5b which is 21 m from the nearest creek. Plate 16, located on the edge of the largest creek in the study site, has a lower sedimentation rate than Plate 17, located 10 m from the edge of the same creek. Plate 10, also located on the largest creek, has amongst the lowest rates on the site with 1.7 cm y^{-1}. The low rates experienced by Plates 16 and 10 are related to creek morphology, being located above the slumped banks of the largest creek. The slumped banks consist of two forms: a discrete stepped morphology and a series of fallen blocks consolidated by vegetation (see Plate 6.1).

Plate 6.1 Stepped bank morphology in Southwick creeks

Tidal waters overbanking these plates deposit appreciable quantities of sediment on the slumped bank and vegetation blocks within the creek. Less sediment is thus available for upper bank sedimentation and this may explain the absence of a levee around the creek. Such forms are frequently found on other marshes.

Clearly evident, is that within the creeks, large amounts of sediment is deposited and eroded. Plates 12 and 13 on the slumped banks of the largest creek, have sedimentation rates of 8.6 cm y^{-1} and 2.7 cm y^{-1}. The very high rate experienced at Plate 12 is likely to be the result of sediment being deposited on the slump bank as a consequence of sediment released by continued slippage of the stepped block. The apparent high rates of sedimentation also hide the fact that these areas also erode because of frequent inundation, often during each tide. In the case of Plate 13, the net accretion over 8 months was 5.8 cm y^{-1} and over 22 months was 4.9 cm y^{-1}, indicating reduced sedimentation or erosion between the two surveys. Steers (1977) suggests that stepped morphology of creeks is related to a higher percentage of sandy rather than muddy sediment. At Southwick this may also help account for the copious movement of sediment within the creek because fine sands are more conducive to entrainment than sediment of a more muddy nature.

As indicated in the aims, this investigation seeks to establish the nature of sedimentation using different methods operating over different timescales to assess whether the patterns of sedimentation change over time. To this end, the pattern of specific activities for ^{137}Cs and ^{241}Am calculated for a number of cores taken from Southwick Merse can be utilised.

6.2.2 Sedimentation rates and patterns derived from radionuclide specific activity profiles

6.2.2.1 Determination of sedimentation rates utilising radionuclide specific activities

Within intertidal sediments around the Irish Sea, radionuclide profiles, their pattern qualitatively comparable to the pattern of Sellafield discharge, have been investigated and used to determine sedimentation rates (e.g. Aston and Stanners, 1979; Stanners and

Aston, 1981a; Clifton and Hamilton, 1982; MacKenzie and Scott, 1982, 1983; Allan *et al.,* 1991). A peak in specific activity in sediments equating to peak discharges from Sellafield during the mid 1970s has been used as a marker to determine the rate of sedimentation since the peak discharges: the deeper the peak in the accumulating sediments, the more accretion has occurred. Clifton and Hamilton (1982) suggest that if there is no radionuclide peak present in the intertidal sediments, the dominant physical process occurring on the marsh is not simple accretion.

MacKenzie *et al.* (1994), calculated sedimentation rates of 4.9 cm y^{-1} and 2.8 cm y^{-1} for positions in Southwick Merse by comparing the ^{137}Cs, ^{241}Am and $^{239,240}Pu$ subsurface maxima of two cores (Allan, 1993; Ben Shaban, 1989), with peak discharges from Sellafield during 1973-75. The overall rates were calculated by averaging the rate determined for each radionuclide.

This procedure can be repeated for the cores extracted from Southwick, the results for which are given in Table 6.1. There are four cores which demonstrate distinct subsurface maxima for ^{137}Cs and ^{241}Am (Figure 5.3) and this can be used to determine sedimentation rates for those cores. The peak discharge of ^{137}Cs from Sellafield was in 1975 and 1974 for ^{241}Am. The cores were analysed in 1996.

Core	Depth of maxima (cm)		Sedimentation rate (cm y^{-1})		Average sedimentation rate (cm y^{-1})
	^{137}Cs	^{241}Am	^{137}Cs	^{241}Am	
SWB	49	49	2.3	2.2	2.2
SWG	59	65	2.8	2.9	2.8
SWJ	53	65	2.5	2.9	2.7
SWK	29	29	1.4	1.3	1.3

Table 6.1 Calculated sedimentation rates based on Southwick cores

These results show that, with the exception of Cores SWB, the decrease in the sedimentation rate from Core SWG, located in the middle marsh, towards SWK, located in the high marsh, corresponding well with the results attained from the sedimentation plates. These rates are minimum estimates, assuming that the peak activities given in the sediment occurred contemporaneously with peak Sellafield discharges. However, MacKenzie *et al.* (1994) modelled a temporal offset between peak discharges and the peak activities found in two cores excavated from Southwick described previously as 'lag times' (e.g. Stanners and Aston, 1981c, Jones *et al.,* 1988, Kershaw *et al.,* 1990). Peak radionuclide activities in an accumulating sediment occur at some time after peak discharges as dictated by the 'input' of radionuclides to the sediment, determined by the Sellafield discharge, and the 'output' of radionuclides from processes of radioactive decay, redissolution and dispersion/dilution (see Figure 2.5). Those radionuclides which are subject to high rate of removal from the offshore sediment because of a short half-life and high amounts of redissolution, will exhibit peak activities shortly after peak discharges have occurred. This is the case with ^{137}Cs. For radionuclides such as ^{241}Am where the output is lower, the peak activities will occur temporally distant from the peak discharges. MacKenzie *et al.* (1994) calculated that peak activities found in intertidal sediments in the Solway Firth would occur in 1978 for ^{137}Cs and 1975 for ^{241}Am. These dates appear contrary to the previous statements because the peak discharge for ^{137}Cs was 1975 and 1974 for ^{241}Am, suggesting that peak ^{137}Cs activities occurred long after peak discharges. It must however be remembered that the inputs to the system must also be taken into account. Whilst the peak ^{137}Cs discharge occurred in 1975, continuing high discharges of ^{137}Cs did not abate until 1978. Therefore the model predicts that peak activities in accumulating sediments occurs very quickly after discharges are reduced.

In light of the temporal offset predicted, the sedimentation rates quoted above of 4.9 cm y^{-1} and 2.8 cm y^{-1} by MacKenzie *et al.* (1994) were recalculated to 6.5 cm y^{-1} and 3.2 cm y^{-1} respectively. Similarly the sedimentation rates for the cores in the present study were recalculated and this is shown in Table 6.2.

Core	Depth of maxima (cm)		Sedimentation rate (cm y^{-1})		Average sedimentation rate (cm y^{-1})
	^{137}Cs	^{241}Am	^{137}Cs	^{241}Am	
SWB	49	49	2.7	2.3	2.5
SWG	59	65	3.3	3.1	3.2
SWJ	53	65	2.9	3.1	3.0
SWK	29	29	1.6	1.4	1.5

Table 6.2 Recalculated sedimentation rates for Southwick cores

In order to determine the manner in which Southwick saltmarsh has developed sedimentation rates derived from the plates and the cores must be compared. Difficulties exist in comparing the sedimentation rates determined from these different sources. Pye and French (1993) note that a distinction must be made between short term deposition of sediment and long-term accretion, the latter representing the difference between total deposition and erosion over a given time interval. Erosion of the marsh surface will generally occur during high energy conditions, especially if these affect the marsh before the most recently deposited sediment has time to consolidate. Rates calculated from short term deposition may thus be higher than rates established from a longer term source because periods of erosion may not be taken into account. Bieniowski (1999), investigating sedimentation rates on Orchardton Marsh, noted that sedimentation rates calculated from 1 tidal inundation were significantly higher than rates determined from data collected over 15 tidal cycles. Stevenson *et al* (1986, 1988), suggest that marsh elevation changes established from short term data will be over-estimated in areas where auto-compaction is high, such as in organic-rich marshes. Harrison and Bloom (1977) state that the amount of compaction which will occur in a marsh is directly related to the organic content and inversely related to the amount of sand.

In this study it is not thought that the rates of sedimentation determined from the plates are over-estimated for two reasons. Firstly, the sedimentation rates established from the plates in this study were calculated over a two year time period. In this time the marsh was subject to a wide variety of tidal and weather conditions exposing it to likely periods of erosion which, had they not been included, would result in over-estimation of the sedimentation rates. Secondly, Southwick marsh is not highly organic and is generally sandy (30% - 40% of sediment at Southwick is greater than 63 μm) thereby reducing the amount of auto-compaction. Indeed, Pye and French (1993) state that in British marshes rates of organogenic sedimentation rarely exceed 0.1 cm y^{-1}.

While the rates established from the plates may be a true reflection of recent sedimentation, the rates established from long term data may be problematic, especially where the sedimentation rate is time-dependent and reduces over time as the height of the marsh increases (French, 1995b). A direct comparison can be made of sedimentation rates determined from the cores and those from plates in similar locations, thereby allowing the change in sedimentation rate over time to be determined (Table 6.3).

Core	Sedimentation rate (cm y^{-1})	Plate	Sedimentation rate (cm y^{-1})
SWB	2.5	25	2.3
SWG	3.2	10	1.7
SWJ	3.0	5b	2.0
SWK	1.5	2	1.3

Table 6.3 Comparison of sedimentation rates derived from Southwick cores and plates

In making this comparison the error margins on the calculations have to be considered. The error on the sedimentation rates derived from the plate results is ± 0.1 cm which reflects the measuring technique outlined in Chapter 4 (4.5.2). The sedimentation rate calculation using the depth of radionuclide maxima is of a similar margin (± 0.2 cm). The depth used to make the calculation was the average of the depth increment used. Each core increment analysed covered 2 cm of the core, therefore the position of a maxima could occur with any part of that 2 cm increment. For example in the case of SWB, the actual depth of the maxima could be anywhere between 50 cm and 48 cm, which would result in a sedimentation rate for ^{137}Cs of 2.67 – 2.78 cm y^{-1}.

Leaving SWB aside for the moment (the specific activities in the radionuclide profile are much lower than the other three cores), Table 6.3 demonstrates that Cores SWG, SWJ and SWK exhibit higher sedimentation rates than determined from the plates, although the difference in SWK and Plate 2 is within the error limits identified above. This higher rate is to be expected since there will be a decrease in the sedimentation rate with time as the height of the marsh increases (e.g. Kestner, 1975; Pethick, 1981, Pye and French, 1993) because of a lower hydroperiod and consequently a lower sediment supply (Carter, 1988). Pethick (1981) suggests that sedimentation rates will reduce to practically zero when the marsh is subject to modal tides.

By comparing the average rates established from the plate data and the core sub surface maxima (Table 6.3), minimum estimates for the reduction in sedimentation rates over time for Cores SWG, SWJ and SWK of 0.075 cm y^{-2}, 0.05 cm y^{-2} and 0.01 cm y^{-2} are evident; the lowest yearly reduction in sedimentation rates is associated with the more mature marsh. However, the rates given in Table 6.3 are *average* rates, and include high rates associated with sedimentation occurring 20 years ago when the marsh was at a lower height, together with low rates associated with contemporary sedimentation. While the contemporary sedimentation rates are articulated by the plate results, there is no indication of the sedimentation rates associated with the older marsh surface.

The results for Core SWK are interesting in that the yearly reduction in sedimentation suggests that the marsh may be close to its maximum height associated with modal tides (Pethick, 1981 suggests that marshes subjected to modal tides will have a sedimentation rate of nearly zero). However, a sedimentation rate of 1.3 cm y^{-1} for a high marsh area is somewhat higher than rates experienced in other U.K. marshes (Pethick, 1981). From the analysis of sequential maps (Figure 5.1) it is apparent that this part of the marsh is at least 100 years old. According to Pethick (1981), the accretion rate for a marsh of this age should be somewhere in the region of 0.48 cm y^{-1}. Not only is the sedimentation rate higher than expected but it has been maintained at this level for at least 10 years despite an inevitable increase in marsh height. If it is accepted that the plate data are not over-estimating the sedimentation rate, there may be enhanced sedimentation occurring on the high marsh. This may occur in two ways: increases in the relative sea level or sedimentation as a consequence of storm activity.

With regard to the first of these scenarios, it is questionable whether Southwick is experiencing increased relative sea level. Although global sea level rise* may be up to 3.5 mm y^{-1} (Pethick, 1984), Shennan (1989) calculates that the south-west of Scotland is experiencing crustal uplift of the region of 0.96 mm y^{-1} resulting in a drop in relative sea level rise of 0.4 mm y^{-1}. Therefore, maintenance of this part of the high marsh may be a consequence of enhanced sedimentation resulting from high spring tides or storms (French and Spencer, 1993; Hayden *et al.,* 1995) rather than normal tidal conditions. However Hansom (1999) notes that increases in global sea level will firstly be evident in enhanced storm influence, thereby affecting the rear of the marsh. Qualitative evidence of storm activity in the form of a trash line on the landward side of the marsh indicates that this part of the marsh is inundated under extreme tidal and weather conditions.

The sedimentation rates evident on Southwick show a distinct pattern. Not only is there a decrease in the sedimentation rate towards progressively higher parts of the marsh, but a decrease in the sedimentation rate, on all parts of the marsh, through time. This analysis has utilised the existence of a distinct peak in radionuclide specific activities found in three of the cores. Clifton and Hamilton (1982) noted that if such a peak was found in intertidal sediments, the dominant physical process was probably sediment accretion rather than other processes such as mixing. Six of the Southwick cores do not feature a defined subsurface radionuclide maximum, suggesting that the accretionary regime presented above is influenced by other processes. Hutchinson and Prandle (1994) also pointed out that comparison of core profiles from the same marsh can illustrate the development history that marsh regardless of the presence of a radionuclide peak.

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* Sea level changes range from stability to 3.5 mm y^{-1} but it must be appreciated that there are significant regional variations (Pethick, 1984).

6.2.2.2 Determination of sedimentation patterns utilising radionuclide specific activities

As indicated above, the absence of a peak in specific activity in most of the Southwick cores indicates, according to Clifton and Hamilton (1982), a complex sedimentation pattern, perhaps involving processes such as mixing and erosion in addition to accretion. That the radionuclide specific activities are not linearly related to the Sellafield discharge limits their interpretation, however there are some important points to consider.

The existence of radionuclides in all cores to a depth of 1 m (with the exception of SWJ and SWK) and the fact that, in those cores not exhibiting a peak, the specific activity increases with depth, indicates that both the mudflat and saltmarsh have been accumulating sediment for some time since Sellafield discharges reduced from their peak levels. The absence of a peak and the gradual increase in specific activity suggests that accretion is indeed the dominant process and that the accretion is rapid.

In addition to this very simplistic observation it appears apparent that radionuclide specific activities are higher on the established saltmarsh compared to the mudflat or pioneer marsh. This observation is in agreement with Horrill (1983) who noted radionuclide concentrations on saltmarsh to be 2 – 3 times higher than on mudflat and was attributed to a decrease in sediment size. Whilst the sediment size data collected in this study cannot confirm this particular aspect, there is an apparent relationship between the radionuclide specific activity and organic content (% loss on ignition) of the sediments. Indeed, research indicates that in intertidal sediments high values of organic content are associated with the finest sediments and these in turn exhibit the highest radionuclide activities (Hetherington, 1978; Aston *et al.,* 1981; Assinder, 1983). Table 6.4 compares the mean ^{137}Cs and ^{241}Am specific activities of the top 10 cm of each core (thereby largely avoiding the influence of activities associated with elevated discharges from Sellafield), with mean % loss on ignition. The results reveal that higher activities are almost consistently associated with a higher organic content and that these correspond to the more mature parts of the marsh.

The extent of the relationship between organic content and specific activity cannot be established by simply comparing high radionuclide values with high organic content values because of the influence of peak activities associated with high Sellafield discharges. However, it can be established by comparing the profiles of the two data sets (Figures 5.2 and 5.3 respectively). A feature of both sets of data is the existence of a number of peaks and troughs in data values extending the length of the cores: a feature which overlaps the peak activities associated with higher discharges. Comparison of the depths at which the peaks and troughs in both data sets occur shows that they are, in many cases, coincident. An example of this comparison method is shown in Figure 6.1.

Core	^{137}Cs (Bq kg^{-1})	^{241}Am (Bq kg^{-1})	% Loss on ignition
SWA	125	101	2.6
SWB	233	207	3.2
SWC	186	167	3.8
SWD	173	168	2.6
SWE	145	122	2.1
SWF	217	209	3.7
SWG	246	167	3.6
SWH	222	193	3.0
SWJ	228	234	5.0
SWK	270	253	3.7

Table 6.4 Comparison of radionuclide specific activities with organic content

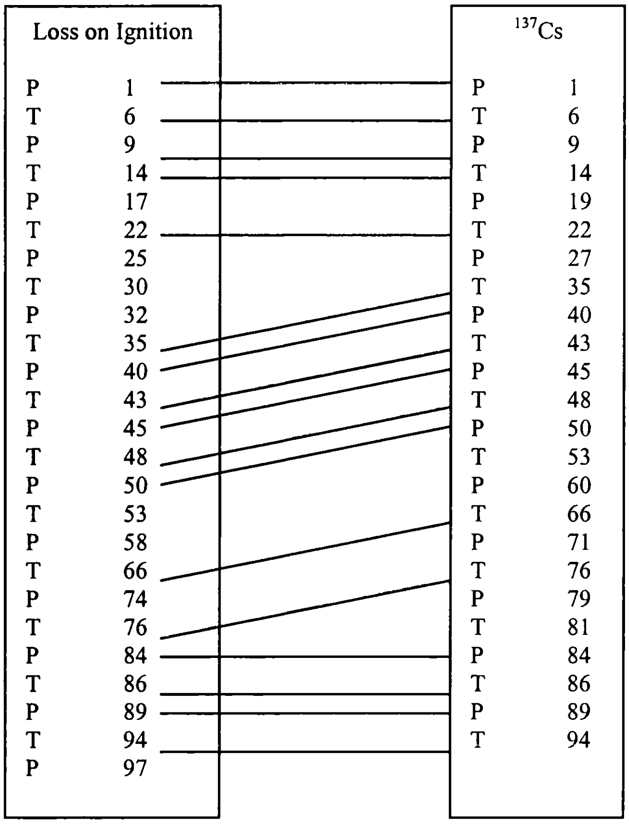

Figure 6.1 Comparison of value turning points in Core SWA (P – Peak, T – Trough)

This method of comparison is unsophisticated but it does illustrate a very strong relationship between high radionuclide specific activities and higher organic contents. This relationship is evident in all the Southwick cores.

In section 5.1.5 the main pattern identified in the organic content data was the existence of peaks and troughs in the data and it was suggested that this resulted from a sedimentation regime in which organic rich sediment is deposited between phases of organic poor sediment deposition. The above analysis necessitates a sedimentation regime which will also facilitate deposition of radionuclides.

During tidal inundation of Southwick Merse, the (relatively long*) vegetation is often flattened by the force of the water surging over the creeks and the front of the marsh, especially if the inundation is associated with high spring tides or storms. This has the effect of trapping the fine grained sediment, occupying the vegetation leaves and stems, between the flattened plants. The sediment occupying positions on the saltmarsh plants will be very fine grained because it is filtered directly from suspended sediment within the flood tide: larger particles will be deposited by direct settling from the flood tide close to the edge of the creeks. It is with these very fine particles, especially clay, that radionuclides are particularly associated (e.g. Aston and Stanners, 1981; Assinder, 1983; Jones *et al.,* 1984). The flattened vegetation will eventually begin to decay as successive tides, and sediment, wash over it. This, then, provides an organic rich layer included with which is a source of very fine grained sediment and associated high concentrations of radionuclides.

This interpretation does not, of course, apply to the non vegetated mudflat areas. In these instances, it is possible that finer sediment (and thus radionuclides) is trapped by thin layers of algal material which occupies and binds mudflat sediments. Clay particles will be more tightly bound to the algal material because of their electrostatic properties.

The cores considered in this section have, thus far, been analysed using the pattern of specific activities to determine sedimentation rates and, to a limited extent, patterns. While this is a valid qualitative interpretation, there are inherent problems comparing the Sellafield discharge directly with the core radionuclide profiles because they are not linearly related (MacKenzie and Scott, 1993).

As illustrated in section 6.2.2.1, where a discrete peak exists, sedimentation rates can be determined by using the appropriate temporal offset for particular radionuclides. In the absence of a peak the radionuclide activities in the sediment profile cannot be compared to the Sellafield discharge and therefore cannot be dated by this means. MacKenzie *et*

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* Southwick Merse is grazed only by wildfowl resulting in vegetation remaining long unlike the cropped swards which are evident on saltmarshes grazed by livestock.

al. (1994) suggest that in an accumulating deposit being supplied by the mixed pool of contaminated sediment in the Irish Sea, radionuclide activity ratios at any given depth will be some constant fraction of the activity ratios of the discharge integrated to the year of deposition of the sediment, taking into consideration the differences in geochemical behaviour of the different radionuclides used. For instance, account must be taken of post-depositional decay, ingrowth (in the case of ^{241}Am) and re-dissolution (in the case of ^{137}Cs). By using the ^{137}Cs/^{241}Am activity ratios, a more rigorous test is available to determine the pattern of sedimentation occurring on the marsh. Utilisation of radionuclide activity ratios is not reliant on the existence of sub-surface maxima and enables interpretation of marsh processes other than sedimentation rate.

6.2.3 Sedimentation rates and patterns on Southwick derived from radionuclide activity ratios

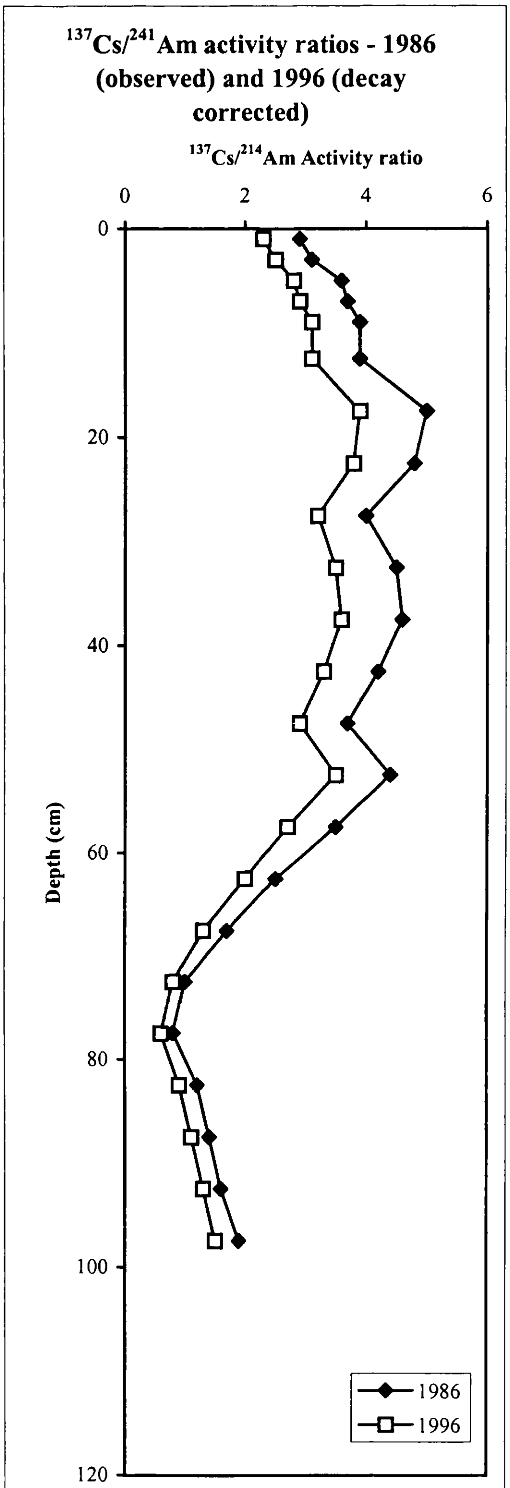
6.2.3.1 Radionuclide activity ratio background information and template cores

In order to investigate patterns of sedimentation in Southwick marsh using radionuclide activity ratios, it is necessary to determine the extent to which activity ratios of the Sellafield discharge have changed over time. MacKenzie *et al.* (1994) noted a systematic decrease in the ^{137}Cs/^{241}Am activity ratio found in intertidal sediments relative to the time-integrated discharge since the 1970s, resulting from a loss of ^{137}Cs relative to ^{241}Am. The loss is a consequence of the dissolution of ^{137}Cs during transport of sediment in the Irish Sea and decay of ^{137}Cs relative to ^{241}Am. The resulting reduction in the ^{137}Cs/^{241}Am activity ratio over time means that sediment found to have a high ^{137}Cs/^{241}Am activity ratio can be interpreted as being older (see p.265 for details).

The most efficient way to account for these processes is to use a template illustrating the changes in activity ratios manifest in the saltmarsh sediments. Two cores, taken from Southwick marsh upstream of the current study area in 1986 and 1989 (Ben Shaban, 1989, Allan, 1993, MacKenzie *et al.,* 1994) are available to provide a template, the ratios being indicative of an accumulating sediment capturing the character of the peak Sellafield discharges. Before an accurate comparison can be conducted, the activity ratios for the two template cores must be decay-corrected to 1996, the time the cores in the present study were analysed. The results of this are shown in Table 6.5 and Figure 6.2.

1986 Core			1989 Core		
Depth	$^{137}Cs/^{241}Am$ activity ratio		Depth	$^{137}Cs/^{241}Am$ activity ratio	
(cm)	Observed	Decay-corrected	(cm)	Observed	Decay-corrected
0-2	2.9	2.3	0-5	2.0	1.7
2-4	3.1	2.5	5-10	2.1	1.8
4-6	3.6	2.8	10-15	2.9	2.5
6-8	3.7	2.9	15-20	3.5	3.0
8-10	3.9	3.1	20-25	4.2	3.6
10-15	3.9	3.1	25-30	4.0	3.4
15-20	5.0	3.9	30-35	3.4	2.9
20-25	4.8	3.8	35-40	2.7	2.3
25-30	4.0	3.2	40-45	2.1	1.8
30-35	4.5	3.5	45-50	2.5	2.1
35-40	4.6	3.6	50-55	3.0	2.5
40-45	4.2	3.3	55-60	4.5	3.8
45-50	3.7	2.9	60-65	11.9	10.1
50-55	4.4	3.5	65-70	20.6	17.5
55-60	3.5	2.7			
60-65	2.5	2.0			
65-70	1.7	1.3			
70-75	1.0	0.8			
75-80	0.8	0.6			
80-85	1.2	0.9			
85-90	1.4	1.1			
90-95	1.6	1.3			
95-100	1.9	1.5			

Table 6.5 Decay-corrected (to 1996) and observed $^{137}Cs/^{241}Am$ activity ratios for 1986 and 1989 Southwick cores (original data from MacKenzie *et al.*, 1994)



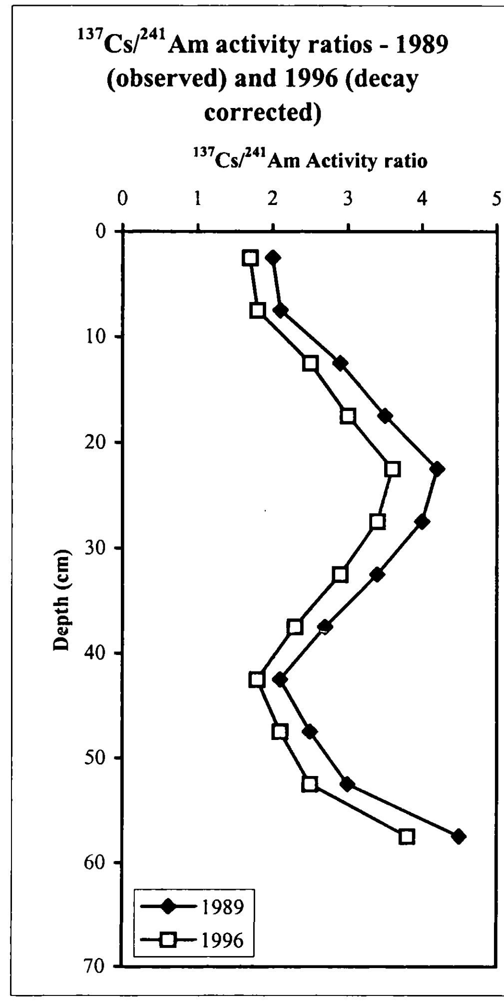


Figure 6.2 Decay-corrected and original $^{137}Cs/^{241}Am$ activity ratio profiles for Southwick Merse (1986 and 1989)
(original data from MacKenzie *et al.,* 1994)

The resultant $^{137}Cs/^{241}Am$ activity ratio profiles for the two cores, after decay-correction, should be similar if the two template cores experienced the same depositional and post-depositional conditions.

Both template cores exhibit an expected subsurface peak in $^{137}Cs/^{241}Am$ activity ratio because of the linear relationship with the integrated Sellafield discharge. However, examination of the profiles shows a systematic decrease in the $^{137}Cs/^{241}Am$ activity ratios between the two cores suggesting a loss of ^{137}Cs relative to ^{241}Am from 1986 to 1989. Each core also shows an increase in the ratio at depth which does not correspond to the pattern of discharge. These characteristics are presented in Table 6.6.

Profile characteristics	1986 core	1989 core
Surface ratios	> 2	< 2
Peak ratios	> 3 – 3.9	3 – 3.6
Lowest ratios at depth	< 1	1.5
Increased ratios at depth	1.5	> 10

Table 6.6 $^{137}Cs/^{241}Am$ activity ratio characteristics (decay-corrected) for template cores

MacKenzie *et al.* (1994) indicate three processes which will reduce the specific activity of a radionuclide in Irish Sea offshore sediments: radioactive decay, dispersion/dilution and redissolution. The decrease in the $^{137}Cs/^{241}Am$ activity ratio between the two cores is evident on the decay-corrected curves, meaning that decay cannot be attributed to the loss of ^{137}Cs in the 1989 core. Secondly, once sediment is deposited and consolidated on a marsh, there is little resuspension of that sediment and since there are clear sub-surface maxima evident in the cores, it can be presumed that no post-depositional mixing causing dispersion or dilution of the ^{137}Cs has occurred. This leaves dissolution.

Numerous works illustrate that ^{137}Cs in the Irish Sea sediments is subject to redissolution (e.g. Jones *et al.,* 1988; MacKenzie and Scott, 1993; MacKenzie *et al.,* 1994) however, there is little evidence to suggest that significant redissolution occurs after deposition on intertidal areas. Indeed, Pulford *et al.* (1998) suggest that the ^{137}Cs in intertidal sediments is associated with the residual phase of the sediment and is, therefore, unlikely to experience redissolution. Livens and Baxter (1988) suggest that only physical processes are important in ^{137}Cs transport but if this were the case, then the ^{241}Am in the sediment would also be moved. The K_D (the partition coefficient – a measure of the potential for a radionuclide to adsorb to sediments) value for ^{137}Cs in the Solway intertidal sediment is calculated at 10^5 L Kg^{-1} (Pulford *et al.,* 1998) which is 10 times lower than the K_D of ^{241}Am, 10^6 L Kg^{-1} within Irish Sea sediments, suggesting that theoretically, there will be more dissolution of ^{137}Cs than ^{241}Am. In Irish Sea sediments MacKenzie *et al.* (1998) established that re-dissolution of ^{137}Cs did occur from offshore Irish Sea sediments but that the extent of the dissolution decreases with depth. The greater amount of ^{137}Cs dissolution at the surface of the seabed sediments was attributed to low quantities of ^{137}Cs in the overlying water body as a result of reduced discharges. Whilst it must be noted that chemical and physical conditions within the Irish Sea are significantly different from those in a saltmarsh, it is plausible that tidal water flushing through sediment interstices will promote dissolution of ^{137}Cs. Even though the actual amount of ^{137}Cs moving down the sediment profile may not be large, it is likely to exceed the movement of ^{241}Am, resulting in an increase in the subsequent $^{137}Cs/^{241}Am$ activity ratio. Evidence of dissolution is twofold. An increase in $^{137}Cs/^{241}Am$ activity ratios occurs at depth in the two cores, suggesting that ^{137}Cs is accumulating deeper in the sediment profile. Also the 1989 core has higher $^{137}Cs/^{241}Am$ ratios at depth (below the ratio peak) compared to the 1986 core. As suggested by Mackenzie *et al.* (1998) there appears to be less redissolution progressively down the sediment profile.

If the pattern of dissolution exhibited in these template cores is extrapolated, the cores in this current study should have a peak $^{137}Cs/^{241}Am$ ratio of about 2.9.

It is suggested above that whilst evidence of high ratios indicates older sediment and low ratios indicate young sediment, dissolution progressively affects older sediments with depth. In the standard cores taken in 1986 and 1989, there is a distinct sub-surface peak below which there are mainly low ratios. In an unknown stratigraphy there is no way of knowing whether a low ratio is associated with very young or very old sediment, although comparison of the ratio with the specific activity levels should indicate 'younger' sediment having a much higher ^{241}Am level. However, sediment found at the top of a profile is generally younger than the sediment found at depth and if no peak occurs in the $^{137}Cs/^{241}Am$ activity ratio, it can be assumed that the sedimentation occurred after the peak radionuclide discharges (or via uncontaminated sediment). Low ratios below a peak in the $^{137}Cs/^{241}Am$ activity ratio can be assumed to be related to sediment deposited prior to the peak radionuclide discharges. There is, however, another aspect of this to be considered.

A clarification of the term 'younger' must be made to distinguish between sediment which is recently deposited on the surface of the saltmarsh and sediment which has been recently contaminated. Sediment which has been recently contaminated will have low $^{137}Cs/^{241}Am$ specific activity ratios relating to those in the source pool of contaminated sediments in the Irish Sea. Sediment being deposited on the surface of the marsh , may however, come from a source of sediment contaminated with radionuclides when discharges from Sellafield were much higher, therefore exhibiting higher specific activity ratios. A likely scenario in this case is material being eroded from one part of a saltmarsh and re-deposited on the surface of another part of the marsh.

The dissolution of ^{137}Cs may also pose a potential problem for the interpretation of the $^{137}Cs/^{241}Am$ activity ratios. Sediment found with high ratios can be assumed to be of an age equating the date of the peak radionuclide discharges. However, high activity ratios are also associated with sediment deposited prior to the peak discharges and affected by ^{137}Cs which has been transported through the sediment profile, due to redissolution. High ratios found within a sediment profile attributed to the effect of redissolution will have appreciably lower radionuclide specific activities than that associated with peak radionuclide discharges. Therefore, interpretation of the activity ratios must be done with reference to the corresponding specific activities.

In order to calculate sedimentation rates from the $^{137}Cs/^{241}Am$ activity ratios, the chronology of the activity ratios for the template cores must be established. Using the peak radionuclide activities, average sedimentation rates for the two template cores are 6.5 and 3.2 cm y^{-1}. Using these sedimentation rates, the date of the peak $^{137}Cs/^{241}Am$

activity ratio can be calculated. For both template cores, the midpoint of the $^{137}Cs/^{241}Am$ activity ratio peak (rather than the highest activity ratio) was dated at around 1981/82.

The above discussion has provided tools with which to analyse the $^{137}Cs/^{241}Am$ activity ratios exhibited in each of the 10 cores excavated from Southwick. Using the activity ratios will further facilitate determination of sedimentation rates experienced on the Southwick marsh but, perhaps more excitingly, will facilitate investigation of those cores which do not exhibit sub-surface maxima.

6.2.3.2 Determination of Southwick sedimentation rates utilising $^{137}Cs/^{241}Am$ activity ratios

Of the 10 cores, six exhibit a peak in $^{137}Cs/^{241}Am$ activity ratios (Figure 6.3). Table 6.7 illustrates the sedimentation rates derived from the peak ratios in these cores. The sedimentation rates were calculated using 1981 as the earliest time from which peak ratios would have accumulated on the marsh. In all cases, the central point of peak activity ratios was used rather than the highest ratio value which created problems because the peaks in some cores are not well defined.

Core	Peak $^{137}Cs/^{241}Am$ activity ratio - midpoint depth (cm)	Sedimentation rate (cm y^{-1})
SWB	44	2.9
SWF	67	4.5
SWG	41	3.1
SWH	59	3.9
SWJ	40	2.7
SWK	23	1.5

Table 6.7 Sedimentation rates for Southwick cores utilising $^{137}Cs/^{241}Am$ activity ratios

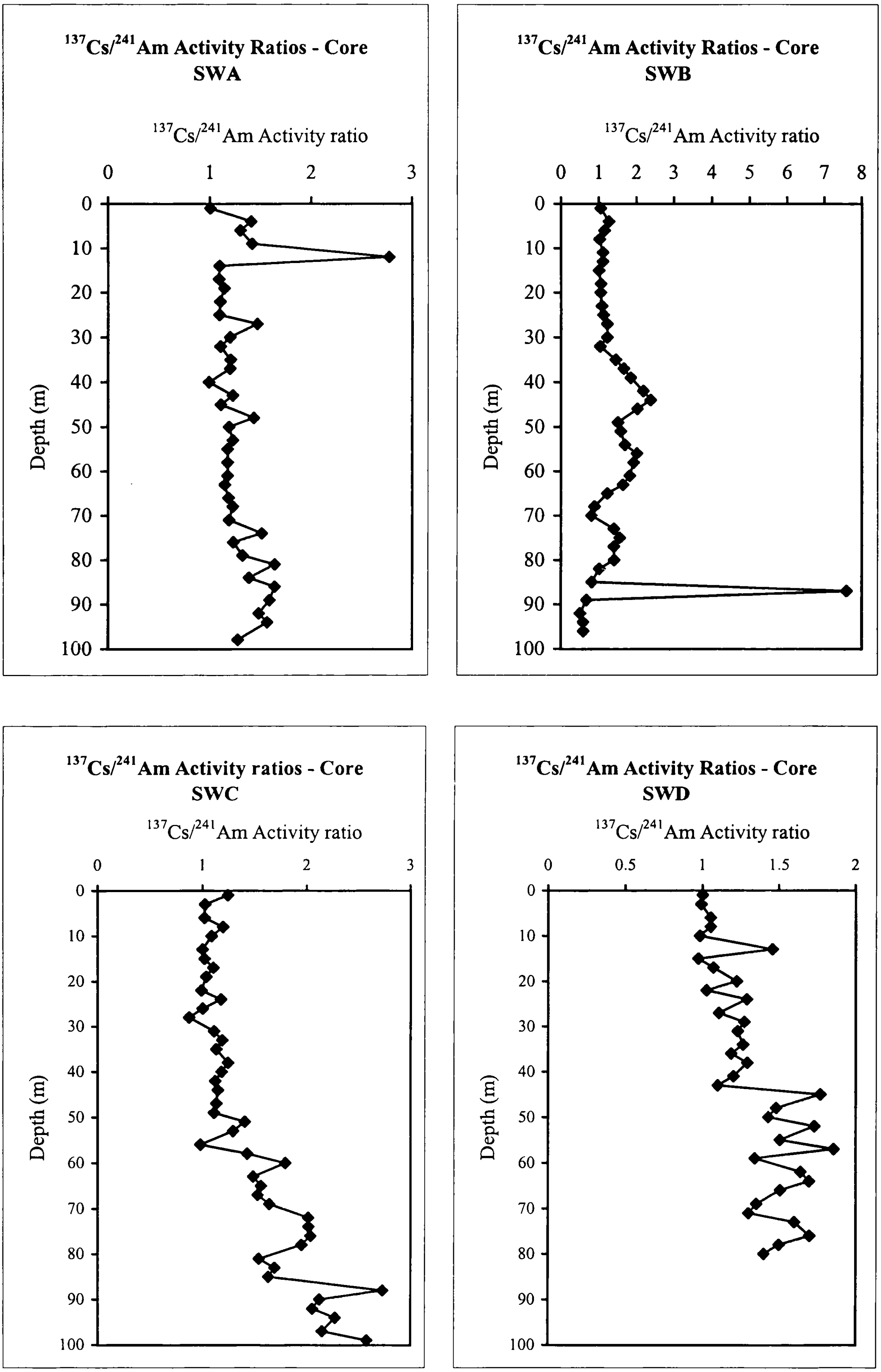


Figure 6.3 $^{137}Cs/^{241}Am$ **Activity ratio profiles - Cores SWA, SWB, SWC, SWD**

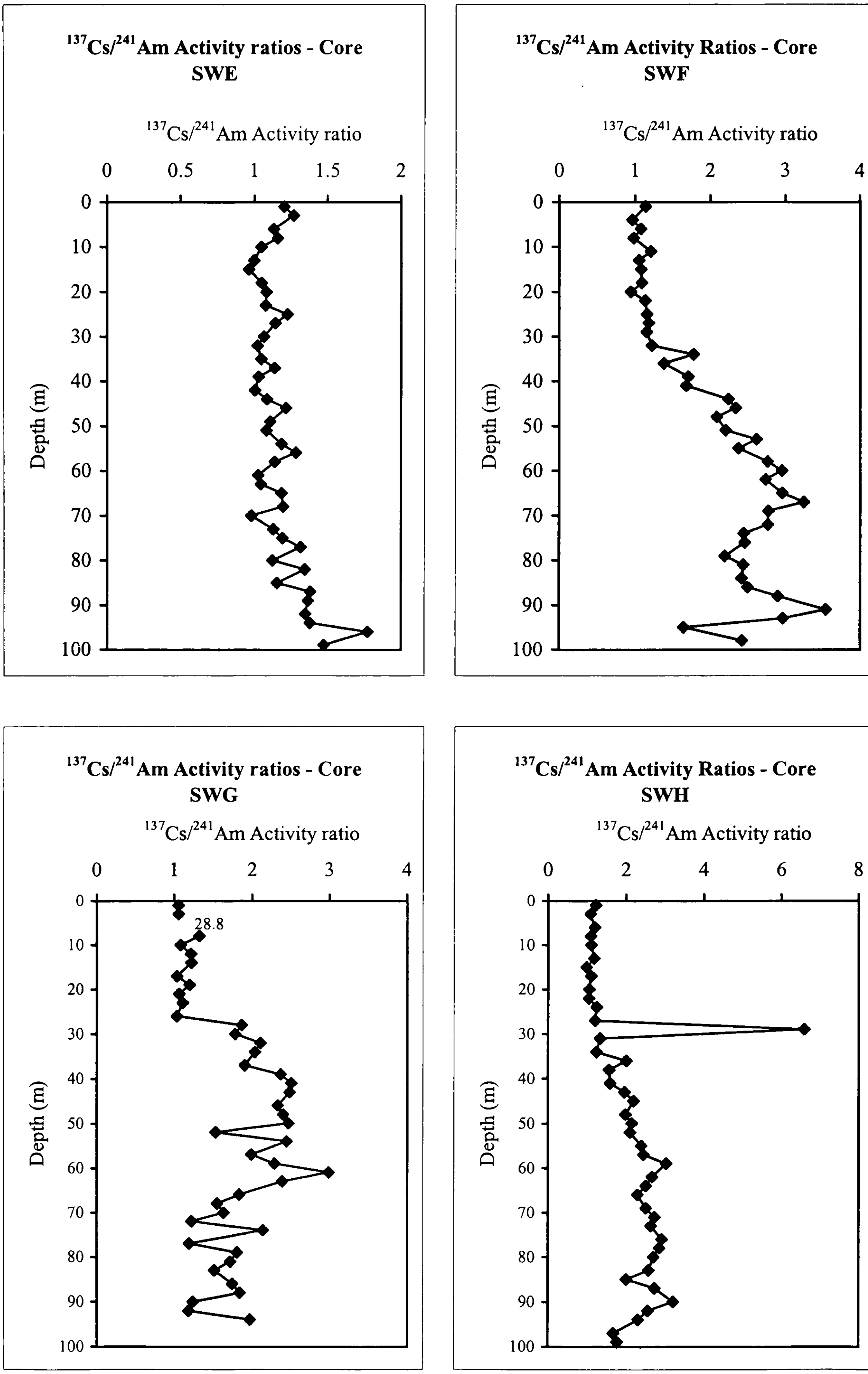
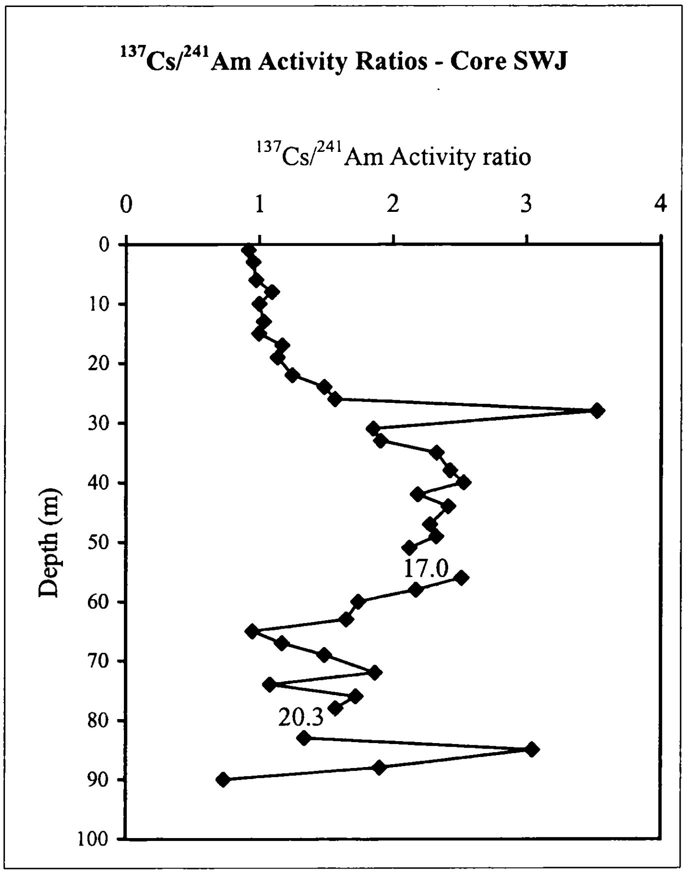


Figure 6.3 (cont.) $^{137}Cs/^{241}Am$ Activity ratio profiles - Cores SWE, SWF, SWG, SWH



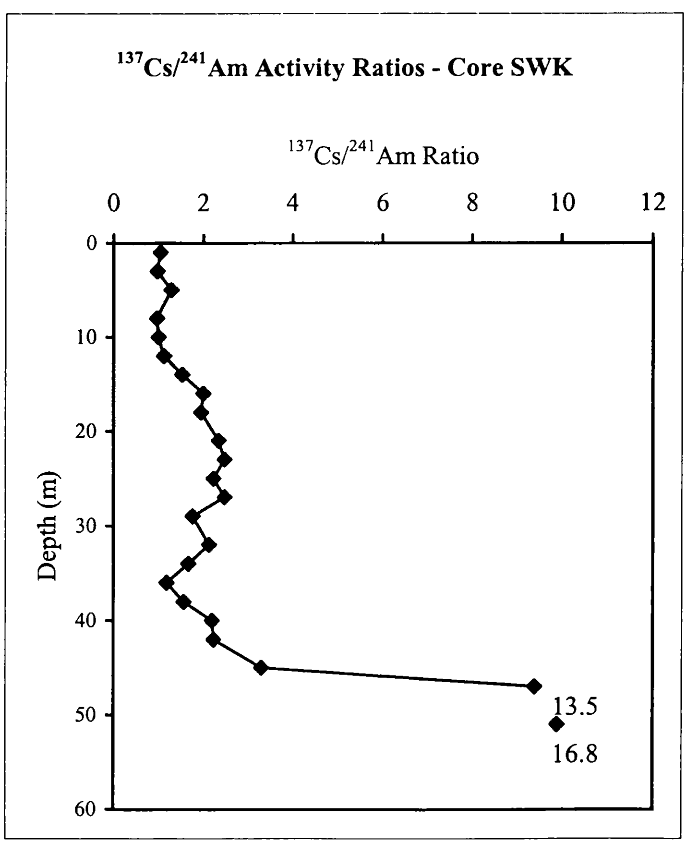


Figure 6.3 (cont.) $^{137}Cs/^{241}Am$ Activity ratio profiles - Cores SWJ, SWK

Core SWB located on the mudflat has a relatively low sedimentation rate reflecting mudflat erosion and accretion. SWF located 30 m from the front of the marsh next to a large creek exhibits the highest sedimentation rate, indicating a high hydroperiod in this part of the marsh. Cores SWG, SWJ and SWK indicate a progressive lowering of sedimentation rate indicating a reduction in tidal inundation towards the landward side of the marsh. The rate for SWH is relatively high reflecting that it is both proximal to a creek and is inundated, to a small extent, by Southwick Water.

Whilst these patterns are consistent with the literature, it is necessary to determine whether they are also consistent with the sedimentation rates already established. The sedimentation rates for Cores SWG, SWJ and SWK (from Table 6.7) can be plotted, together with the rates derived from the sedimentation plates and specific activity profiles (from Table 6.3), onto the sedimentation rate curves to verify (or otherwise) the consistency of the data (Figure 6.4). The resultant curves demonstrate that there is indeed a decrease in sedimentation rates with time consistent with that proposed in the literature. The addition of a trendline indicates the reduction is strongly linear.

In section 6.2.2 sedimentation rates derived from the plate data (Plate 1) were higher than expected from the sedimentation rates derived from core SWK. The rates determined from the $^{137}Cs/^{241}Am$ activity ratios also suggest this. High contemporary sedimentation rates were argued to result from storm activity rather than normal tidal action and so the expected sedimentation rate was higher than expected. While this idea is compelling, more data are required to substantiate it.

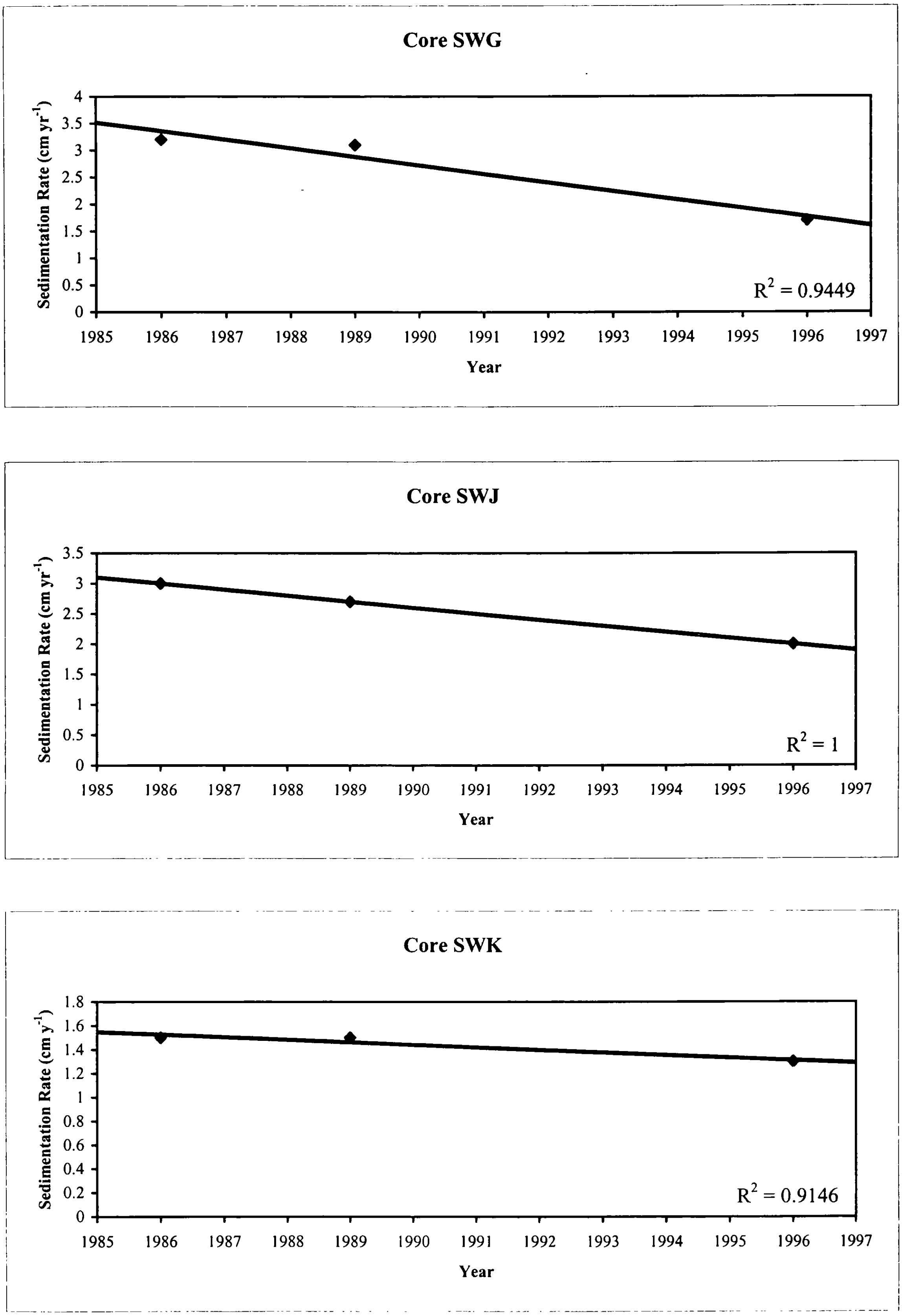


Figure 6.4 Sedimentation rates for Cores SWG, SWJ and SWK over time

If increased storm activity were instrumental in maintaining enhanced sedimentation rates an associated increase in sediment size can be anticipated due to the higher competence of the water flooding the marsh. A comparison of sediment characteristics for cores (upper 50 cm) located in the middle and high marsh are given in Table 6.8.

Core	Sediment size		
	% < 63 μm* (sieve data)	% < 63 μm! (Coulter data)	% < 3.9 μm (Coulter data)
SWG	54.8	79.5	7.9
SWH	59.4	72.7	6.7
SWJ	46.2	78.2	6.8
SWK	51	77.6	7.6

Table 6.8 Sediment characteristics (derived from dry sieving and laser diffraction) of Cores SWG, SWK, SWJ and SWK

The results indicate that the Cores SWJ and SWK, located the furthest inland, have the coarsest sediment, with the least amount of material passing through a 63 μm sieve. In addition to this SWK has a high percentage of clay (< 3.9 μm) which suggests that once clay sized material is carried onto the high marsh it is deposited rather than re-entrained. This is expected because of the energy difference in flood and ebb tide. Presumably this disparity would be enhanced if the flood water were associated with stormy conditions. However, the data are far from conclusive and further work is required to determine the case for and cause of enhanced sedimentation on the high marsh.

* Values indicate the percentage of sediment, from the entire sample, passing through 63μm sieve.

! Values indicate particle size as determined using laser diffraction. The sample analysed is from material which has been passed through a 63μm sieve.

6.2.3.3 Interpretation of Southwick sedimentation patterns utilising $^{137}Cs/^{241}Am$ activity ratios

The interpretation of sedimentation patterns using the ^{137}Cs/^{241}Am activity ratios requires the chronology of ratio changes in relation to Sellafield integrated discharges to be established. MacKenzie *et al.* (1994) note a systematic decrease in the ^{137}Cs/^{241}Am activity ratio as a consequence of the loss of ^{137}Cs relative to ^{241}Am via radioactive decay and redissolution. In an accumulating sediment, the profile of ^{137}Cs/^{241}Am ratio will compare to Figure 6.2, notably exhibiting a sub-surface maximum. If a peak is not present, it can be assumed that processes other than simple accretion are at work (Clifton and Hamilton, 1982). In an accumulating sediment, ^{137}Cs will undergo dissolution resulting in a reduction, over time, of the ^{137}Cs/^{241}Am activity ratio. Extrapolation of the Southwick template cores (p.265) indicates that peak ^{137}Cs/^{241}Am ratios in the region of 2.9 can be anticipated. In a sediment which has undergone rapid mixing, there will be a homogenisation of activity ratios (MacKenzie *et al.*, 1998). Contemporary ^{137}Cs/^{241}Am activity ratios in Irish Sea surface seabed sediments are around 1 (MacKenzie *et al.*, 1998), a figure which should be reflected in sediments recently deposited at Southwick.

For clarity the marsh discussion which follows will be divided into four sections, each representing a distinct geomorphological unit of the marsh. The ^{137}Cs/^{241}Am activity ratio profiles for the 10 Southwick cores are presented in Figure 6.3.

- Mudflat - Cores SWA, SWB
- Middle marsh (< 10 m from marsh front) - Cores SWC, SWD, SWE
- Middle marsh (10 - 70 m from marsh edge) - Cores SWF, SWG, SWH, SWJ
- High marsh - Core SWK

Mudflat

The ^{137}Cs/^{241}Am activity ratio profiles for Cores SWA and SWB appear quite different. Core SWA exhibits a slight increase in ^{137}Cs/^{241}Am ratio values with depth, whereas SWB displays a distinct sub-surface maximum. The progressive increase in ratio values with depth in Core SWA indicates that, not surprisingly, sediment has accumulated over time. In core SWA, however, the $^{137}Cs/^{241}Am$ ratio between the depths of 11 cm and 71 cm exhibits little variation with values in the range 1.0 – 1.5, with a mean of 1.1 +/- 0.24. There are two small peaks at 27 cm and 48 cm which have values of 1.5 and 1.4 respectively. These values are comparable with the top 32 cm of core SWB which has a mean value of 1.1 +/- 0.08. The relative homogeneity of these two core sections indicate the sediments, although generally accumulating, have been well mixed and have been deposited at Southwick in the recent past. This is entirely expected in mudflat sediments which are subject to rapid and frequent tidal inundation.

However, the $^{137}Cs/^{241}Am$ activity ratio values of the surface sediments of core SWA are somewhat higher than the mean of SWB 1.1, ranging from 1.0 to 2.8. These higher values suggest that while there may be mixing of the sediment, the source is older sediments that have been contaminated with the Sellafield discharge and may not come recently from seabed sediments from the Irish Sea. In this context the probable source of this sediment is from recycling of sediment from an eroding part of either this, or another, saltmarsh.

The $^{137}Cs/^{241}Am$ subsurface maximum in core SWB tells another story. The SWB profile, below the depth of 35 cm displays a peak which bears a striking resemblance to the template core excavated in 1986 (Figure 6.2) suggesting that the lower parts of SWB may be saltmarsh sediments rather than mudflat sediments. The peak $^{137}Cs/^{241}Am$ activity ratio value at 45 cm is 2.4, lower than might be expected based on the values of the template cores but it can be anticipated that, because of the current location on the mudflat, fluctuating tidal water and groundwater levels may increase the rate of ^{137}Cs redissolution. Given the sharp boundary between the homogenous upper sediments, the sub-surface maximum and the variation below a possible interpretation may be that the upper core represents mudflat over the lower saltmarsh. The core was excavated less than 6 metres from the eroded edge of the marsh and based on the ratio evidence this area was in fact once saltmarsh. At some point after 1981 (the time in which peak $^{137}Cs/^{241}Am$ ratios were deposited) erosion occurred, moving the front edge of the marsh landward. The area eroded became mudflat accumulating sediment which was intensely mixed. This interpretation is supported by the fact that none of the cores from the front edge of the current saltmarsh (SWC, SWD, SWE) has a subsurface maximum, indicating these sediments accumulated after the deposition of the highest Sellafield ratios. In addition, sedimentation rates from the plate results (Plate 21) also indicate that the marsh surface, given contemporary rates of accretion, would have been at the level of the subsurface maximum indicated in SWB, around 1981.

Middle marsh (< 10 m from marsh front) - Cores SWC, SWD, SWE

In Cores SWC, SWD and SWE, there are increases in the $^{137}Cs/^{241}Am$ activity ratio with depth but no subsurface maxima are evident. This suggests that the sediment accumulation occurred subsequent to the deposition of peak ratios during the early 1980s. In all three cores the upper sections exhibit ratios showing little variation. The mean values in SWC, SWD and SWE are 1.09 +/- 0.09, 1.16 +/- 0.14 and 1.11 +/- 0.1, respectively. The homogeneous nature of these ratios also suggests that the sediment was either well mixed or simply accreted rapidly from a homogenised source. Given the fact that these cores were excavated from an accreting saltmarsh, the latter is more plausible. Certainly, the available contemporary sedimentation rates associated with this area (Plates 18, 20, 21) are all very high.

The lower sections of Cores SWC, SWD and SWE exhibit much higher ratios reflecting that the sediment was deposited soon after peak ratios from Sellafield. Only SWC has a ratio approaching 2.9, suggested from the template cores as the likely maximal ratio value, taking redissolution of ^{137}Cs into account. The lower sections of these cores also exhibit moderately fluctuating ratios, a pattern not commensurate with mudflat environments or rapidly accreting sediments. The mean values in these lower sections are 1.81 +/- 0.4, 1.55 +/- 0.17 and 1.4 +/- 0.2 for Cores SWC, SWD and SWE respectively. This type of fluctuation is exhibited in the template core S1 (and is illustrated in the other Southwick cores) and therefore reflects a pattern consistent with established saltmarsh. The patterns illustrated in the lower parts of these three cores therefore suggest that the seaward end of this marsh has been subject to erosion (soon after the deposition of high Sellafield activity ratios) and has subsequently enjoyed rapid vertical accretion. The lower parts of the cores represent the older marsh sediments whilst the upper sections reflect the newer, rapidly accreted sediments.

Middle marsh (10 - 70 m from marsh edge) - Cores SWF, SWG, SWH, SWJ
The three cores excavated from the central parts of the marsh, with the exception of the top 30 cm, all exhibit $^{137}Cs/^{241}Am$ activity ratio maxima, with values around 3. Some of the $^{137}Cs/^{241}Am$ activity ratios exhibited are very high and in order to maintain the clarity of the graphs, these values have been added as text.

The upper parts of Cores SWF, SWG, SWH, SWJ have mean $^{137}Cs/^{241}Am$ activity ratio values of 1.11 +/- 0.09, 1.13 +/- 0.09, 1.14 +/- 0.08 and 1.05 +/- 0.1 respectively again illustrating rapid sediment accretion. Below this are older sediments which, as well as exhibiting higher activity ratios, also have more widely fluctuating ratios. The activity ratio profiles suggest that around 1986, the marsh underwent a change. Again, the suggestion is that a period of erosion stripped the surface sediments whilst leaving intact the majority of the accumulated saltmarsh sediments. The marsh then began to accrete rapidly, hence the nearly homogeneous ratios in the upper cores.

There is good geomorphological evidence to support this hypothesis. Firstly, around 6 m inland of Core SWJ exists a small cliff demarcating the boundary between the middle marsh and high marsh. This cliff is likely to relate to a period in which the marsh edge has been eroded (Allen, 1989), although the mechanism for this is now unclear. Secondly, there are no salt pans in the middle marsh despite being numerous on the high marsh. Pans are formed in a variety of ways: either during marsh initiation due to the uneven nature of sediment deposition and plant colonisation (circular in shape) or because old creeks become blocked (linear in shape) and are common in the Solway (e.g. Yapp *et al.,* 1917; Chapman, 1974; Pethick, 1974). If the middle marsh area was stripped only of its upper sediment layers, as is suggested by the presence of the high $^{137}Cs/^{241}Am$ activity ratios, it is likely that any pans would be removed and be replaced by more spatially uniform deposition. In other words, pans may be inherited features that have not yet developed on the 'new' marsh surface. This form of erosion is evident on other marshes in the Solway Firth. The vegetation types on the upper marsh differ from that of the middle marsh. For example, minimal *Festuca* and an abundance of the pioneer species *Puccinellia* suggests relatively recent colonisation of the middle marsh.

In each case where there is a very high $^{137}Cs/^{241}Am$ activity ratio the data show an unusually low ^{241}Am specific activity compared to adjacent sediments, rather than an unusually high ^{137}Cs specific activity, the reasons for which are unclear.

High marsh - Core SWK

The $^{137}Cs/^{241}Am$ activity ratio profile for this core bears the closest resemblance to the template cores S1 and S2. The upper few centimetres of the core have ratios around 1. There is a distinct subsurface maxima with a peak ratio of 2.5, slightly lower than would be expected from the template cores. It is possible that a greater amount of redissolution of ^{137}Cs has occurred because of fresh water, rather than tidal waters which may contain ^{137}Cs, moving through the marsh at this point. This is perhaps the only part of the study area which has not been subject to a period of erosion since the accumulation of sediments contaminated with Sellafield discharge.

The patterns shown in the $^{137}Cs/^{241}Am$ activity ratio profiles are themselves interesting and will be discussed further in the following section.

6.2.4 Analysis of patterns in $^{137}Cs/^{241}Am$ activity ratio data

There are a number of extremely high ratios indicated on some of the graphs resulting in disproportionately high ^{137}Cs levels compared to ^{241}Am. It is interesting to speculate that these may be associated with fallout connected to the Chernobyl accident which would show high levels of ^{137}Cs without an associated ^{241}Am component. However, the activity levels are significantly higher than would be expected from Chernobyl fallout. While this possibility for the high activity ratios must be discarded, no further explanation, other than an error in the radionuclide analysis, can be offered.

In all the cores the $^{137}Cs/^{241}Am$ activity ratio profiles indicate an increase in ratio values towards the base of the cores. This increase is related to high ^{137}Cs specific activities compared to the corresponding ^{241}Am specific activities. The template cores presented in Figure 6.2 also demonstrate this feature and this is attributed to the down core movement of ^{137}Cs resulting from re-dissolution. Authors suggest that while the redissolution of ^{137}Cs is a phenomenon which occurs in the Irish Sea environment (e.g. Jones *et al.,* 1988; MacKenzie *et al.,* 1994), there is little evidence of this occurring within saltmarsh sediments (Allan, 1993; Pulford *et al.,* 1998). The results presented here illustrate that there is indeed re-dissolution of ^{137}Cs occurring in the upper parts of the core which is then re-deposited towards the base of the core.

This can be explained with reference to the equilibrium of ^{137}Cs between contaminated sediment and the downwards percolation of relatively uncontaminated water through the saltmarsh deposits (Figure 6.5).

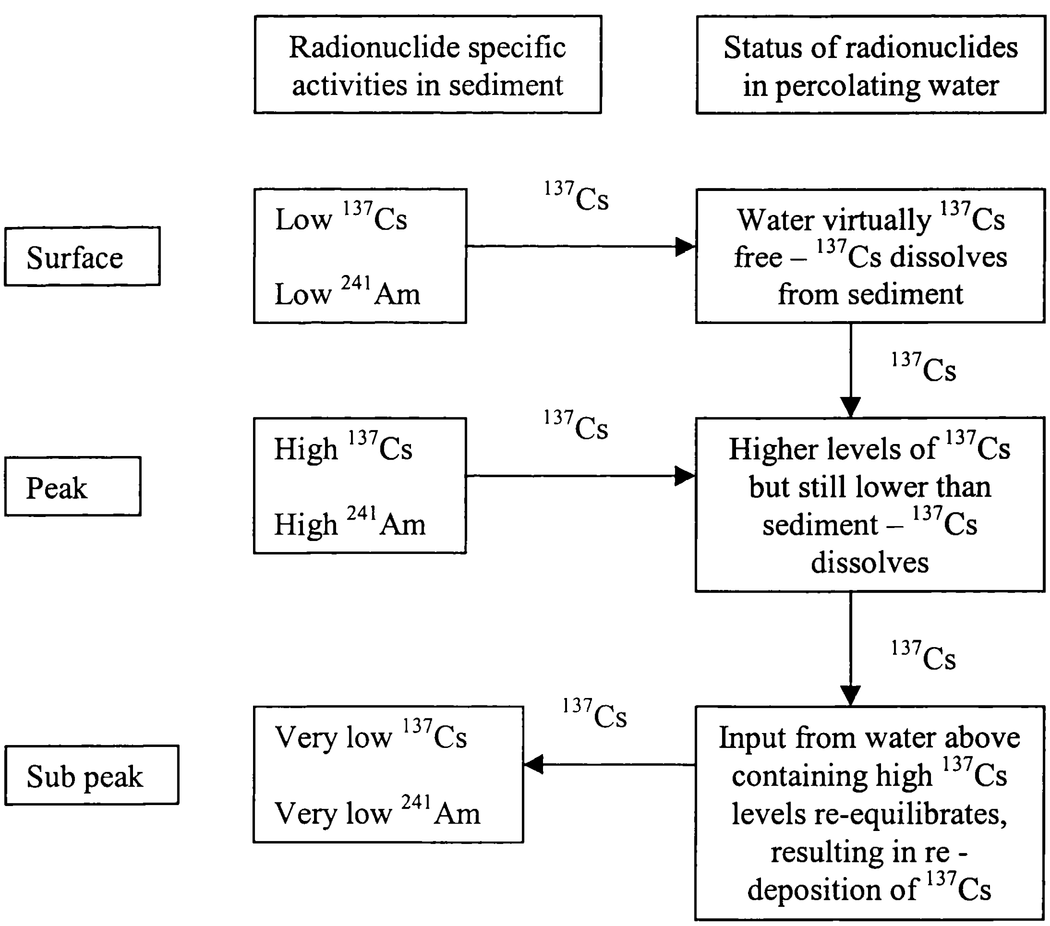


Figure 6.5 Model explaining re-dissolution of ^{137}Cs in saltmarsh sediments

At the surface of the marsh, the virtually ^{137}Cs free water moves through sediment which contains, although low, significant concentrations of ^{137}Cs, resulting in re-dissolution. The dissolved ^{137}Cs moves through the sediment profile with the percolating water until a position in the profile where the concentrations of ^{137}Cs in the sediment are extremely low compared to the that in the water. This results in ^{137}Cs being re-deposited within the sediment.

These results indicate therefore that contrary to Livens and Baxter (1988), it is not only physical processes that are important in the transport of ^{137}Cs in saltmarshes: chemical processes also play an important role.

6.2.5 Radionuclide inventories

The above analysis has concentrated on using radionuclide specific activities as a tool to investigate sedimentation patterns and processes. Determination of those processes can also facilitate greater understanding of the radionuclide distributions. To this end, the radionuclide inventories for ^{137}Cs and ^{241}Am will be discussed in the context of the geomorphological processes which are evident on the saltmarsh system.

For comparison with the results in the present study, Table 6.9 provides a summary of inventories calculated for Southwick Merse by Allan (1993). In Allan's study, the cores with a sub surface peak in specific activities relating to high Sellafield discharges, exhibited this peak within the top 30 cm. In the present study, the peak appears deeper in the sediment profile, thereby illustrating different sediment rates.

Distance (m) from Mean High Water*	0 – 15 cm of core		15 – 30 cm of core		Total inventory in top 30 cm of saltmarsh	
	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})
-3	58 481	30 097	1 926	849	60 407	30 946
0	126 527	39 181	212 469	76 836	338 996	116 017
10	97 487	47 287	217 260	75 532	97 704	122 819
20	267 451	78 814	37 553	5 953	305 004	84 767
30	58 853	15 290	5 515	1 339	63 368	16 629
40	26 195	5 717	4 341	905	30 536	6 622
50	27 798	3 833	5 436	856	33 234	4 689
70	16 545	907	5 740	BDL	22 285	907

* Positive numbers indicate a movement landward

BDL – Below Detection Limit

Table 6.9 Inventories for Southwick Merse calculated by Allan (1993)

Table 6.10 summarises the inventories calculated for the 10 cores excavated from Southwick Merse in the present study.

Core	Depth of analysis (cm)	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})
SWA	98	44 771	34 891
SWB	96	114 016	84 990
SWC	99	135 567	90 516
SWD	80	80 437	60 099
SWE	99	72 227	61 411
SWF	98	203 340	97 060
SWG	99	262 030	145 388
SWH	99	227 634	107 316
SWJ	90	205 904	111 113
SWK	53	133 860	73 201

Table 6.10 Calculated inventories for Southwick Merse cores

The two tables of figures are comparable: the highest inventories are shown in the central areas of the marsh with values over 200 000 Bq m^{-2} for ^{137}Cs and 100 000 Bq m^{-2} for ^{241}Am. The inventories in the present study are perhaps slightly higher than those presented in Allan (1993), thereby confirming that inventories in accumulating saltmarshes are set to increase despite the reduced discharges from Sellafield, although it must be appreciated that the inventories in the present study are calculated for a deeper sediment profile.

The lowest inventories are present in mudflat sediments and the areas of pioneer saltmarsh which are rapidly accumulating sediment, e.g. Cores SWA, SWD and SWE. Inventories are at their highest in the middle marsh areas where there is the presence of sub surface maxima relating to high Sellafield discharges but are also areas which are rapidly accreting sediment.

The high marsh areas in this site, Core SWK, has significantly higher inventories than the samples shown furthest inland by Allan (1993) because it is still actively accreting sediment which is contaminated with Sellafield discharge. This emphasises the importance of determining the accretionary status of intertidal sediments before interpreting radionuclide inventories.

6.3 Orchardton

6.3.1 Sedimentation rates and patterns derived from plate results

Sedimentation patterns at Southwick largely conform with observations reported in the literature which state that the highest sedimentation rates occur at the seaward end of a saltmarsh, reducing inland with increased height and marsh maturity. Patterns at Orchardton cannot be as satisfactorily explained, because the highest sedimentation rates are recorded not only in the mudflat areas but also at locations furthest inland. In addition to apparent inconsistencies in the general sedimentation pattern, the net accretion values are not as expected. Ranwell (1964a) cites numerous studies illustrating sedimentation rates attributed to differing vegetation species: 3 cm y^{-1} was recorded in low *Salicornia* marsh in Norfolk; 0.2 cm y^{-1} accretion was recorded on a Danish *Puccinellia* marsh. These figures are significantly lower than the 10 to 12 cm y^{-1} accretion recorded by Ranwell on *Spartina* marshes at Bridgewater Bay, Somerset. From these, and other similar figures, it was anticipated that sediment accretion on the *Spartina* marsh at Orchardton would exceed values from other marshes such as Southwick, which support *Puccinellia* as a pioneer species.

In order to compare Orchardton with the literature, discussion of the sedimentation pattern will be divided into two sections. The first will deal with the mudflat and vegetated pioneer marsh (both *Salicornia* and *Spartina*). The second will concentrate on the more mature *Spartina* marsh.

6.3.1.1 Mudflat and pioneer marsh

The highest sedimentation rates recorded were on the mudflat adjacent to, and on, the *Salicornia* marsh. However, the highest erosion rates were also located in this vicinity. Sedimentation rates on the mudflat surrounding the *Salicornia* marsh (Plates 1, 4 and 8) are 4.9 cm y^{-1}, 7.6 cm y^{-1} and 8.1 cm y^{-1}. Plates 4 and 8 were located on the northern side of the *Salicornia* marsh at a lower altitude than Plate 1 and therefore subject to more frequent tidal inundation and higher sedimentation rates. The more northerly mudflat area is also subject to inundation by two sources of tidal waters: one being a creek within the mudflat (shown on the eastern side of the mudflat on the map – Map 2a) and the second directly from Orchardton Lane which meanders around the western side of the mudflat. These two sources will deliver a greater amount of sediment to the mudflat surface.

On the *Salicornia* marsh itself, sedimentation rates vary from 1.1 cm y^{-1} to –1.3 cm y^{-1} and –1.6 cm y^{-1} (Plates 6, 5 and 3 respectively). The erosion can be explained with reference to the micro-topography of the marsh surface. Plate 3 is located on the northern side of the *Salicornia* marsh and is affected by currents and wavelets as the incoming tides lap up the side of the slope to produce small micro-cliffs nearby. Plate 5 sits at the top of the marsh between two pans which encourage the development of small eddies in the incoming tide (Chapman, 1974), and loss of sediment at this location. Plate 6 on the other hand is on the highest part of the *Salicornia* area away from topographic irregularities suggesting that proximity to such features will determine whether erosion or accretion occurs. Small variations in marsh surface topography therefore have an impact on marsh flooding thereby influencing the pattern of sedimentation (Reed and Cahoon, 1992) whilst, the manner of tidal flooding will influence the micro-topography of the marsh surface (Frey and Basan, 1985).

The accretion values recorded on the *Salicornia* marsh and on the pioneer *Spartina* marsh are lower than those recorded for the unvegetated mudflat. The pioneer areas of *Spartina* marsh, have accretion rates of 4.1 cm y^{-1} and 2.5 cm y^{-1} (Plates 9 and 12), several cm y^{-1} lower than accretion on the mudflat. This is unexpected because vegetation is generally considered to promote increased sedimentation by reducing wave and tidal energies (Frey and Basan, 1979; Christiansen and Miller, 1993; Möller *et al.*, 1999). French (1999) reports that the colonisation of an unvegetated surface by vegetation will decrease the erosion rate of that surface. This is supported by Randerson (1979) who states that the primary role of *Spartina* is to stabilise the sediment surface, rather than trapping or filtering sediment. In addition to differences in sedimentation between the mudflat and pioneer marsh, the reduced influence of vegetation on sedimentation in Orchardton is dramatically shown by the low sedimentation rates recorded on the established *Spartina* saltmarsh ranging from -0.7 cm y^{-1} to 0.9 cm y^{-1}.

Not only are these values very small compared to rates observed at Southwick, but there appears little variation across the extent of the marsh. Before considering in detail the pattern of sedimentation and low sedimentation rates on the *Spartina* marsh, some discussion is required about factors influencing sedimentation.

It is evident from the data recorded at Orchardton that there are factors other than vegetation which facilitate increased sedimentation on the mudflat compared to the vegetated marsh. The influence of micro-topography has already been discussed. The erosion thresholds of mudflat sediments and vegetated sediments will be determined by biological (for example, vegetation, diatom biomass and algal levels), physical (for example, moisture content and sediment bulk density) and chemical properties (Christie *et al.,* 1999; Houwing, 1999). Williamson and Ockenden (1996) demonstrated a direct relationship between the shear stress of sediments and bulk density. Using this observation, Christie *et al.* (1999), in a study of the Skeffling mudflats (Humber Estuary), postulated that the shear stress of fine upper mudflat sediments would be lower than that of coarser lower mudflat sediments because of a lower sediment bulk density. The authors however discovered that higher erosion thresholds were found in the upper mudflats due to increased diatom concentrations stabilising the sediment. Upper mudflat sediments contain a high percentage of clay sized particles and so have cohesive properties (Rowell, 1994). Mitchener and Torfs (1996) concluded that the critical shear stress for erosion increases when mud* is added to sand and indeed if enough mud is added, the sand will behave as a mud. This behaviour means that the factors affecting erosion of the sediment will include electrochemical forces, mineral composition and organic content, biological processes, composition of the pore water and eroding fluids and the consolidation and time-related histories of the bed. Added to this is the moisture content of the sediment because, as noted in the discussion on the Southwick mudflats (section 6.2.1), sediment which becomes dry between inundations will have a higher shear stress than sediment which remains moist (Amos *et al.,* 1988; Hutchinson *et al.,* 1995).

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* In this instance the term mud is used to denote a sediment size less than 62.5 μm.

The above comments demonstrate that only by comparing chemical, physical and biological factors can the pattern of sedimentation be fully understood. Although a detailed examination of all these parameters is beyond the scope of this study, a brief examination of some factors will outline the complexity of sedimentation processes existing on this marsh. Table 6.11 summarises the sediment size analysis, organic content and accretion rates of sediment located in the mudflat, pioneer *Salicornia* and *Spartina* marsh. The sediment size and organic data are from cores excavated nearest to the corresponding plates.

Core	Plate	Accretion rate (cm y^{-1})	Loss on ignition (%)*	Vegetation status	% sediment less than 63 μm*
ORA	1	4.9	2.61	Unvegetated	64.0
ORB	5 6	-1.3 1.1	2.40	*Salicornia*	66.9
ORC	8	8.1	2.79	Unvegetated	73.6
ORE	12	2.5	3.80	*Spartina*	68.3
* top 2cm of core					

Table 6.11 Summary of factors relating to sedimentation in Orchardton mudflat and pioneer marshes

The above table illustrates that the higher sedimentation rates are found in locations where there is a higher loss on ignition value (representing organic content) and/or a higher percentage of sediment less than 63 μm. The high sedimentation rate recorded at Plate 8 corresponds to a high percentage of mud (term as used by Mitchener and Torfs, 1996). The *Spartina* pioneer marsh has an accretion rate of 2.5 cm y^{-1} with a correspondingly high organic content. The lower organic content value on the *Salicornia* marsh, while surprising given the existence of an algal mat during the summer months (section 5.2.2.1), is likely to reduce the sediment stabilisation thereby encouraging a greater amount of sediment resuspension. Initial discussion of the *Salicornia* marsh attributed the recorded erosion to the influence of micro-topography in addition to the characteristics of the sediment. It should also be noted that the *Salicornia* marsh is at a higher altitude than the *Spartina* pioneer zone which also reduces accretion rate.

Further analysis of the data in Table 6.11 indicates that the *Spartina* pioneer marsh has a higher organic content than mudflat at ORC, yet it has a lower sedimentation rate. This can again be related to the influence of topography. The *Spartina* sedimentation rate (Plate 12) was recorded seaward of a small cliff which marks the boundary between the pioneer and mature marsh. During inundation water laps against the cliff resulting in erosion of the cliff and the fronting mudflat. Over the study period the cliff has slumped and retreated slightly. In addition to this, the area in front of the cliff is almost permanently wet.

The pattern of sedimentation in the mudflat and pioneer areas of the marsh can largely be attributed to tidal interaction with topographic features. The influence of sediment characteristics plays a secondary role in the resultant pattern.

Given the similarity in sediment characteristics between the *Salicornia* marsh and the *Spartina* marsh, it is curious that there is indeed a difference in the colonising species. Scholten and Rozema, (1990) note that *Spartina* has a preference for clayey soils. Randerson (1979) notes that in marshes predominately colonised by *Spartina, Salicornia* may act as a primary coloniser on more sandy foreshores. To address this issue a closer investigation of the sediment size analysis for both pioneer marshes is required (Table 6.12).

Core	Vegetation type	Percentage weight of size fraction in surface sediments				
		coarse silt	medium silt	fine silt	very fine silt	clay
ORB	*Salicornia*	41.51	13.87	9.6	6.34	6.01
ORE	*Spartina*	43.76	12.67	8.2	5.46	5.47

Table 6.12 Summary of surface sediment size analysis of pioneer marsh on Orchardton

Whilst the *Salicornia* marsh has a lower coarse silt content, it does have higher values of medium, fine and very fine silt and it may be this subtle difference in size distribution which accounts for the competitive advantage of the *Salicornia* on this site. Alternatively, the fact that the part of the marsh colonised by *Salicornia* is slightly higher and better drained than the *Spartina* marsh may also account for the difference in colonising vegetation.

The possibility also exists that *Salicornia* may be more efficient at trapping sediment than *Spartina* although this has not been tested and is not apparent in the literature.

Comparisons may be drawn between the mudflat sedimentation patterns at Southwick and those at Orchardton. Sedimentation rates at Southwick are more variable demonstrating periods of erosion and accretion whereas at Orchardton accretion is dominant. This is further expanded in Chapter 7 to identify reasons for the difference between marshes.

6.3.1.2 Spartina *marsh*

Contrary to figures presented in the literature, very low sedimentation rates characterise the whole *Spartina* marsh. Before investigating specific sedimentation rates derived from the plates in the marsh, it is necessary to discuss the pattern of sedimentation expected, derived from simple observation of the geomorphological map and vegetation. As noted in section 5.2.2.2 the *Spartina* marsh topography comprised a hummocky structure, enhanced largely by subtle changes in vegetation density although the heights of the hummocks are usually no more than a few centimetres.

As with the development of any saltmarsh, the progression from mudflat through pioneer marsh to mature marsh may be initially governed by random undulations in the mudflat topography. Areas which are slightly higher, promote increased sedimentation due to reduced tidal flow velocities. As a consequence, these higher areas encourage the establishment of both pioneer and secondary vegetation more rapidly than surrounding lower areas. This is certainly the case on Orchardton where only the hummocky areas show evidence of secondary colonisation. Kearney *et al.* (1994) noted that on *Spartina* marshes in eastern Chesapeake Bay, random changes in the marsh micro-topography influenced the distribution of plant species, resulting in a lack of the typical zonation of vegetation species generally expected in saltmarshes. Of interest too is the density of vegetation, especially *Spartina,* which is higher on the hummocks. This increased density may be attributed to reduced hydroperiod and thus salinity (Scholten and Rozema, 1990), but waterlogging of the lower areas may also impede the production of *Spartina* shoots. The density of shoots within the lower areas is less than on the better drained, higher areas.

The increased density of *Spartina* shoots and the development of secondary vegetation suggest that preferential accretion is occurring on the hummocks. At the seaward end of the marsh, Plates 14a, 14b and 16, all of which are located on hummocks, have sedimentation rates of 0.8 cm y^{-1}, 0.7 cm y^{-1} and 0.9 cm y^{-1}, higher than at Plates 15 and 17, located in lower areas, which have rates of 0.3 cm y^{-1} and –0.7 cm y^{-1} respectively. These reduced sedimentation rates may be attributed to both lower vegetation density and waterlogging of the lower areas. This reduces sediment trapping and increases the potential for the resuspension of sediment. Anomalous to this pattern are Plates 18 and 19, both of which are located on hummocks, which show signs of erosion. However, Plates 17 and 18 are located near the head of a small channel which, over the study period, has deepened and retreated into the marsh. This headwards expansion is likely to have resulted in enhanced flows in the area at the head of the marsh and an enhanced likelihood of sediment resuspension.

The influence of creeks on Orchardton can be examined further. On Southwick marsh, sites located next to creeks displayed high sedimentation rates because they were inundated more frequently. At Orchardton, areas located close to the edge of creeks display negative sedimentation rates. For example, Plates 20 and 21 have rates of –0.3 cm y^{-1} and –0.7 cm y^{-1}, respectively. However, those located more than 1 m from the creek edge have low but positive accretion rates: Plates 22 and 25 have rates of 0.2 cm y^{-1} and 0.1 cm y^{-1}. The marsh bordering the creeks displays secondary vegetation (*Puccinellia, Aster maritima* and *Salicornia*) indicating that they are slightly higher than the surrounding marsh, a pattern expected in saltmarshes. Nevertheless, parts of the creek network are expanding with signs of headward erosion and widening and this results in reworking of the higher areas adjacent to creeks and removal of sediment. The existence of the levee areas bordering the creeks suggests that the enhanced accretion that must have occurred in the past is now being reversed by the current accretion rates. It is possible that such levees will not be maintained as the rest of the marsh slowly increases in height and this may affect creek geometry and network.

The areas where consistent signs of accretion (albeit very low rates) exist are those at the landward edge of the study area. Plates 23, 26 and 30 are on slightly lower parts of the marsh where the cover of *Spartina* is quite sparse and have similar rates: 0.5 cm y^{-1}, 0.4 cm y^{-1} and 0.4 cm y^{-1}. The rates on the slightly higher areas (Plates 24, 27 and 31) which have more extensive vegetation coverage are again similar, although slightly higher. The variation between the two areas however are outwith the error limits of +/- 0.1cm y^{-1}. These areas, even the slightly lower areas are predominantly *Puccinellia* rather than *Spartina* colonised and this may assist sedimentation. As noted in the previous section, Randerson (1979) suggests that the primary role of *Spartina* is to stabilise the sediment surface rather than to trap sediment. This function facilitates the initial colonisation of *Puccinellia* within the protection of *Spartina* stands (Scholten and Rozema, 1990). *Puccinellia* is tolerant of the waterlogging that characterises Orchardton Merse. Once established the *Puccinellia* appears to have a superior competitive ability and this is certainly demonstrated on the highest areas of Orchardton Merse. Given the very low or negative sedimentation rates found in areas of the marsh which are colonised only by *Spartina,* it is tempting to suggest that accretion will only occur with any degree of success once *Puccinellia* is established.

Contrary to suggestions by Randerson (1979), experiments conducted on Orchardton Merse (Bienowski, 1999) noted *Spartina* to be very efficient at trapping sediment, and that an inverse relationship existed between sediment deposition from direct settling and that from vegetation trapping (i.e. the higher the density of *Spartina* vegetation, the less direct settling of sediment occurred). In addition to this, it was noted that sedimentation rates calculated from 1 tidal inundation were significantly higher than rates from data collected over 15 tidal cycles (Bieniowski, 1999). This information therefore suggests that while *Spartina* has the capacity to filter sediment from incoming tidal waters it may not be effective at retaining that sediment on the marsh surface. In areas of the marsh where *Spartina* is the only species, there exist areas of exposed wet sediment which, is likely to be resuspended in subsequent tides. Indeed, the base of the *Spartina* reeds may themselves increase turbulence making the incoming waters more efficient at mobilising sediment. However, establishment of *Puccinellia* quickly provides a continuous vegetation cover, protecting the marsh surface and therefore ensuring that resuspension is mitigated. At the same time, the *Puccinellia* may provide an efficient trap for sediment washed from the stems of *Spartina* reeds. Whilst this may appear incongruous with the high accretion rates experienced in the pioneer *Spartina* marsh, the longer hydroperiod experienced by the pioneer marsh may well account for higher sedimentation rates. Moreover, erosion of the marsh edge is likely to supply additional sediment.

The role of *Puccinellia* in trapping sediment is also indicated in the size of sediment which is trapped. Table 6.13 indicates that areas which are colonised by both *Spartina* and other species have a higher percentage of fine grained surface sediment than those colonised by *Spartina* alone, with the exception of ORJ which appears to be anomalous*.

The different sediment trapping mechanisms illustrated by *Spartina* and *Puccinellia* are also indicated in the sub surface sedimentary structures present in the consolidated marsh sediments revealed by the sediment cores excavated from the marshes. The most characteristic structures to be found in marsh sediments are distinct wavy, parallel laminations or thin bedding (Bouma, 1963) indicating that sediment is deposited in layers as tidal waters flood the marsh and interacts with vegetation. These structures are seen at Orchardton in the *Salicornia* marsh, the mudflat sediments and are prevalent in all Southwick Merse sediments. However, except in the top 10 cm of Cores ORH, ORJ and ORK which are also colonised by *Puccinellia,* such structures do not occur in cores excavated from the *Spartina* marsh The absence of lamination suggests that

* Although the surface sediments of ORJ appear to be coarser than other cores in the higher areas of the *Spartina* marsh, the sediment located at 3 cm depth and below is comparable.

sedimentation and erosion on the *Spartina* marsh occurs in an irregular fashion and is not a sequential deposition of sediment with each tidal influx. This observation agrees with the above statement about the sediment retention capabilities of *Spartina* during normal tidal activity.

Core	Plate	Accretion rate (cm y^{-1})	Loss on ignition (%)*	Vegetation status[!]	% silt (less than 63 µm*)	% clay (less than 4 µm*)
ORF	17	-0.7	4.21	20% ***Spartina***	61.3	5.61
ORG	20 22	-0.3 0.2	4.15	20% ***Spartina***	65.9	5.69
ORH	24	0.4	4.99	50% ***Spartina***, *Puccinellia* & *Salicornia*	65.0	7.5
ORJ	27	0.5	2.58	90% ***Puccinellia***, *Salicornia* & *Spartina*	78.5	3.39
ORK	31	0.6	5.00	100% ***Puccinellia***, *Spartina*, *Plantago* & *Triglochin*	66.5	6.37
*Measurement from top 2cm of core ! Dominant species in bold						

Table 6.13 Sediment characteristics of Orchardton marsh

The pattern of vegetation undoubtedly plays a role in the sedimentation pattern but Ranwell (1964a) provides another reason for the higher inland sedimentation rates by suggesting that when accretionary processes are at their peak (August to October), migration of newly deposited sediment occurs from the lower limits of the marsh to upper limits. This is attributed to rising tides prior to the autumnal equinox.

As with the discussion of the mudflat and pioneer marsh, analysis of the sediment characteristics also facilitates understanding of why some areas of the marsh are subject to erosion, while others are able to accrete. Table 6.13 summarises the main sediment characteristics for the mature marsh. The sediment information is from cores excavated in close proximity to the plates under discussion. The data demonstrate that accretion predominates where there are higher percentages of organics, silt or clay. The areas experiencing erosion have low values in all these properties. This would appear to suggest that the cohesive properties of organic material and fine sediment, especially clay, are important factors in ensuring accretion because of increased shear resistance and reduced entrainment following deposition. Once deposited such sediment tends not to be re-entrained (Summerfield, 1991).

Whilst the general pattern of sedimentation can be explained in terms of sediment characteristics, vegetation and topography, the rate of sedimentation is much lower than expected from the literature. One explanation may lie in the timing of the actual data collection. The first set of measurements were collected in June 1996 and the results show very low rates of accretion and some erosion. The second set were collected in August 1997 and in nearly all cases, there is accretion between the two sets of measurements. During the winter and early spring, poor weather conditions such as increased rainfall and storms reduce the overall sedimentation rate. Increased winter rainfall prevents the marsh from drying out, thereby increasing the potential for sediment resuspension. Increased stormy conditions over winter and spring result in recently deposited sediment being eroded from the marsh surface (Christie *et al.*, 1999). The second set of measurements, taken towards the end of the summer, show that some accretion has occurred, which may be due to calmer weather conditions and increased organic material stabilising the sediment. Indeed Ranwell (1964a) suggests that 75% of the accretion occurring on a continuous sward of marsh will occur between August and October.

Although the timing of data collection may have a part to play in the resulting accretion rates, this cannot solely explain the extremely low sedimentation rates, which are a factor of 10 lower than published values. In any case, the accretion rates recorded on the mudflat sediments which presumably would be subject to similar weather conditions as the marsh are higher than expected if the above scenario holds. The most plausible explanation for this is the fact that the marsh is almost continually wet, even during the summer months, and therefore the sediment is susceptible to resuspension (Amos *et al.*, 1988; Reed and Cahoon, 1992). The mudflat areas and the *Salicornia* pioneer marsh are better drained and are more likely to dry out, reducing the opportunity for resuspension.

Reasons for the almost permanently moist state of the marsh are not immediately apparent, although a comparison between the different study sites (Chapter 7) may provide some answers. It could be assumed that areas with high amounts of clay will be prone to waterlogging as the passage of water through the soil structure will be slowed down. However, as noted above, the areas which have the highest amount of clay are also the areas which are less waterlogged and are colonised by secondary marsh vegetation. The waterlogging may also be an artefact of the pathways taken by draining water. The lower areas of the marsh will receive drained water from the higher areas, thereby increasing the volume of water needing to be drained. The wettest areas are those at the head of creeks such as the area between Plates 17 and 18. This suggests that drainage is incomplete before the marsh is re-flooded with tidal waters, and so the marsh is constantly moist.

Examination of the core profile illustrations (as described in section 4.7.3) provides further evidence of the slow draining nature of the Merse. In marshes where there is a rapid throughflow of water and therefore air, conditions facilitate the decomposition of organic debris. In the Orchardton sediments from the *Spartina* marsh, vegetation remains intact throughout the excavated cores to depths of at least 70 cm, indicating anaerobic conditions which, in turn, suggests that water remains in the soil interstices for much of the time. Cores excavated from the mudflat or pioneer *Salicornia* marsh do not display decaying vegetation.

6.3.2 Sedimentation rates and patterns derived from radionuclide specific activity profiles

6.3.2.1 Determination of sedimentation rates utilising radionuclide specific activities

Given the very low contemporary sedimentation rates shown at Orchardton, it is important to determine whether this is a persistent pattern at Orchardton or whether this is a recent phenomenon. According to the Ordnance Survey maps, (Figure 5.5) Orchardton experienced rapid lateral expansion as a result of the *Spartina* planting in

1951 (Pye and French, 1993) but the current sedimentation levels indicate that this expansion period has now ceased and may have been reversed.

In section 6.2.2 historical sedimentation rates for Southwick Merse were estimated using ^{137}Cs and ^{241}Am radionuclide profiles from excavated cores. It was assumed that a peak in the radionuclide specific activity in sediments equates to peak discharges from Sellafield thereby dating the deposition of sediments. In the absence of a radionuclide activity peak in the sediments, it can be assumed that processes other than simple accretion were involved in sediment deposition (Clifton and Hamilton, 1982). MacKenzie *et al.* (1994), calculated sedimentation rates in Southwick Merse by comparing the ^{137}Cs, ^{241}Am and $^{239,240}Pu$ subsurface maxima of two cores (Allan, 1993; Ben Shaban, 1989), with peak discharges from Sellafield during 1973-75. The overall rates were calculated by averaging the rate determined for each radionuclide.

As with the analysis of Southwick, this procedure can be repeated for the cores extracted from Orchardton, the results for which are given in Table 6.14. There are seven cores which demonstrate distinct subsurface maxima for ^{137}Cs and ^{241}Am (Figure 5.7). The peak discharge of ^{137}Cs from Sellafield was in 1975 and 1974 for ^{241}Am. The cores were analysed in 1997.

Core	Depth of maxima (cm)		Sedimentation rate (cm y^{-1})		Average sedimentation rate (cm y^{-1})
	^{137}Cs	^{241}Am	^{137}Cs	^{241}Am	
ORC	88	88	4	3.8	3.9
ORE	35	35	1.6	1.5	1.6
ORF	20	30	0.9	1.3	1.1
ORG	24	29	1.1	1.3	1.2
ORH	26	31	1.2	1.3	1.3
ORJ	54	71	2.4	3.1	2.8
ORK	31	36	1.4	1.6	1.5

Table 6.14 Calculated sedimentation rates based on Orchardton cores

The results indicate that the mudflat and landward marsh areas have the highest accretion rates For the landward marsh this is contrary to the literature (e.g. Letzch and

Frey, 1980; Pethick, 1981; Gray, 1992) which asserts that accretion rates should decrease with increasing marsh maturity. The assumption is that the most mature marsh is located further inland, yet the accretion rates on Orchardton are at least 1 cm y^{-1} lower than those established for equivalent sites on Southwick Merse.

As with the analysis of Southwick, a more accurate calculation of sedimentation rates can be established by invoking a temporal offset between the high radionuclide discharges from Sellafield and peak activities found in the Solway Firth sediments (MacKenzie *et al.,* 1994). The offset, determined by the Sellafield discharge, and processes of radioactive decay, redissolution and dispersion/dilution, results in peak sediment activities being realised in 1978 for ^{137}Cs and 1975 for ^{241}Am. The recalculation of results is given in Table 6.15.

Core	Depth of maxima (cm)		Sedimentation rate (cm y^{-1})		Average sedimentation rate (cm y^{-1})
	^{137}Cs	^{241}Am	^{137}Cs	^{241}Am	
ORC	88	88	4.6	4	4.3
ORE	35	35	1.8	1.6	1.7
ORF	20	30	1.05	1.4	1.2
ORG	24	29	1.3	1.3	1.3
ORH	26	31	1.4	1.4	1.4
ORJ	54	71	2.8	3.2	3
ORK	31	36	1.6	1.6	1.6

Table 6.15 Recalculated sedimentation rates for Orchardton cores

The recalculation produces increased consistency between the rates calculated for the ^{137}Cs and ^{241}Am radionuclides, especially from the cores taken from the mature *Spartina* marsh.

Comparison of the contemporary sedimentation rates derived from the plates and the rates established from the radionuclide activity profiles will indicate how the marsh has developed over 20 years. The same caveats highlighted in the Southwick discussion concerning the validity of making such comparisons, must also be mentioned here. Often it can be demonstrated that sedimentation rates taken over a short timescale will be higher than rates determined over longer periods because periods of erosion and consolidation of marsh sediments are not taken into account (Stevenson *et al.,* 1986; 1988; Pye and French, 1993). It is again noted that the sedimentation rates established using the plates in this study resulted from data collected over two years, thereby periods of erosion were included in the calculation. In addition, the degree of compaction is likely to be minimal because of a relatively high sand content (between 10% and 20% of the core sediments are over 63 μm in size) and relatively low organic content (Harrison and Bloom, 1977).

Sedimentation rates are time dependent, in that there will be a reduction in the sedimentation rate over time as the marsh height, and therefore maturity, increases (Pethick, 1981). There must, therefore, be some expression for the change in sedimentation rates established. Comparison between the contemporary sedimentation rates established from the plates and those calculated from the radionuclide activity profiles of the cores from Orchardton can go some way towards defining this expression.

Core	Sedimentation rate (cm y^{-1})	Plate	Sedimentation rate (cm y^{-1})
ORC	4.3	8	8.1
ORE	1.7	12	2.5
ORF	1.2	17	-0.7
ORG	1.3	20	-0.3
ORH	1.4	24	0.4
ORJ	3	27	0.5
ORK	1.6	31	0.6

Table 6.16 Comparison of sedimentation rates derived from Orchardton cores and plates

It is to be expected that the sedimentation rates from the plates will be lower than those derived from the cores located in the same area because as a marsh increases in height, the hydroperiod and sediment supply are reduced (e.g. Kestner, 1875; Pye and French, 1993). This pattern is demonstrated on all areas of the *Spartina* marsh (Cores ORF -

ORK) but not on the mudflat or pioneer marsh (ORC and ORE respectively). In these two areas it would appear that there is an increase in the sedimentation rate over time. This observation will be explored further.

6.3.2.2 Determination of sedimentation patterns utilising radionuclide specific activities

The profiles of radionuclide specific activities illustrated in Figure 5.7 demonstrate that the sedimentation patterns on the mudflat and *Salicornia* marsh are very different to those on the *Spartina* marsh.

In the *Spartina* marsh cores, the radionuclides are generally contained within the upper 50 cm of the cores. This demonstrates that whilst Orchardton Merse is accumulating sediment, and has done so since the high Sellafield discharges, this process is occurring at a much lower rate than either the mudflat area, or indeed Southwick merse. The profiles also demonstrate that there has been a very slow rate of accretion since the high discharges began to reduce.

The mudflat and *Salicornia* marsh exhibit radionuclides to 1 m in depth although there are no defined peaks. The extent of variability in these profiles is also greater than shown in the *Spartina* cores. As with Southwick, these profiles exhibit a number of peaks and troughs in the data values down the extent of the core which can be matched to corresponding peaks and troughs in the organic content data, indicating that there is a link between the deposition of organic material and high radionuclide concentrations.

There is no such relationship between the organic content data and radionuclide specific activity data for those cores from the *Spartina* marsh. Indeed the radionuclide profiles are very smooth compared to Southwick (even if the different sampling strategies are taken into account) suggesting a different mode of sedimentation. It is proposed above that while *Spartina* is effective at trapping sediment it is unable to retain that sediment on the marsh surface. The radionuclide and organic content profiles demonstrate that sedimentation is slow and systematic, unlike Southwick where there are periods of organic rich (high radionuclide concentrations) and organic poor (low radionuclide concentrations) sediment deposition. It is therefore proposed that deposition of sediment occurs by sediment being washed off the *Spartina* plants or being deposited directly by the tide, but that only a small proportion is retained on the marsh surface.

Core ORK, which has a covering of *Puccinellia,* has a radionuclide profile more akin to those on Southwick, demonstrating the impact of this vegetation to facilitate accretion.

6.3.3 Sedimentation rates and patterns on Orchardton derived from radionuclide activity ratios

6.3.3.1 Determination of Orchardton sedimentation rates utilising $^{137}Cs/^{241}Am$ activity ratios

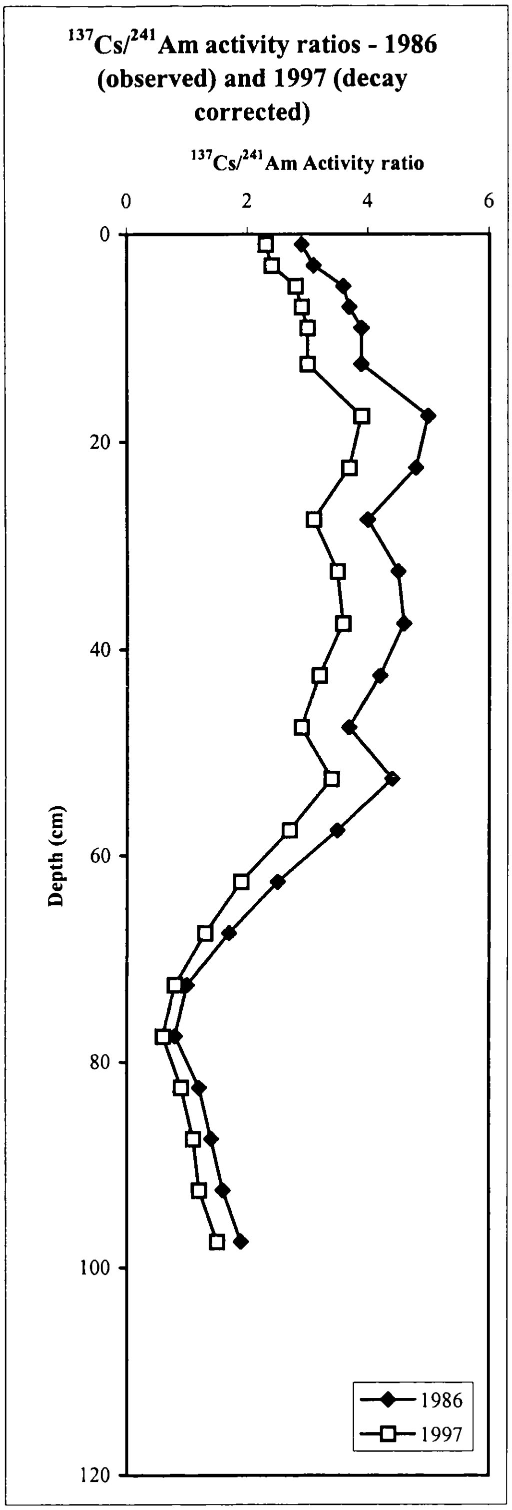
The discussion of Southwick highlighted that using radionuclide specific activities to investigate sedimentation rates and patterns has certain limitations because, the specific activities may not be linearly related to the Sellafield discharge and the absence of a clear sub surface maximum may preclude dating the sediments. Nevertheless, it is possible to utilise radionuclide activity ratios to explore sedimentary processes. Section 6.2.3.1 should be referred to in order to avoid unnecessary repetition.

As with Southwick, a template of the expected $^{137}Cs/^{241}Am$ activity ratio profiles is required in order to draw comparisons with cores excavated from saltmarshes with different sediment dynamics. Unfortunately no such template exists for Orchardton necessitating further use of the Southwick templates derived from MacKenzie *et al.* (1994). The activity ratios for the two template cores have been decay-corrected to 1997, the time the Orchardton cores were analysed. The results of this are shown in Table 6.17 and Figure 6.6.

It has been established that the peak radionuclide activities occurred about 1981/82 therefore providing a date from which to calculate sedimentation rates from the $^{137}Cs/^{241}Am$ activity ratios.

1986 Core			1989 Core		
Depth	$^{137}Cs/^{241}Am$ activity ratio		Depth	$^{137}Cs/^{241}Am$ activity ratio	
(cm)	Observed	Decay-corrected	(cm)	Observed	Decay-corrected
0-2	2.9	2.3	0-5	2.0	1.7
2-4	3.1	2.4	5-10	2.1	1.7
4-6	3.6	2.8	10-15	2.9	2.4
6-8	3.7	2.9	15-20	3.5	2.9
8-10	3.9	3.0	20-25	4.2	3.5
10-15	3.9	3.0	25-30	4.0	3.3
15-20	5.0	3.9	30-35	3.4	2.8
20-25	4.8	3.7	35-40	2.7	2.2
25-30	4.0	3.1	40-45	2.1	1.7
30-35	4.5	3.5	45-50	2.5	2.1
35-40	4.6	3.6	50-55	3.0	2.5
40-45	4.2	3.2	55-60	4.5	3.7
45-50	3.7	2.9	60-65	11.9	9.9
50-55	4.4	3.4	65-70	20.6	17.1
55-60	3.5	2.7			
60-65	2.5	1.9			
65-70	1.7	1.3			
70-75	1.0	0.8			
75-80	0.8	0.6			
80-85	1.2	0.9			
85-90	1.4	1.1			
90-95	1.6	1.2			
95-100	1.9	1.5			

Table 6.17 Decay-corrected $^{137}Cs/^{241}Am$ activity ratios for 1986 and 1989 Southwick cores (original data from MacKenzie *et al.*, 1994)



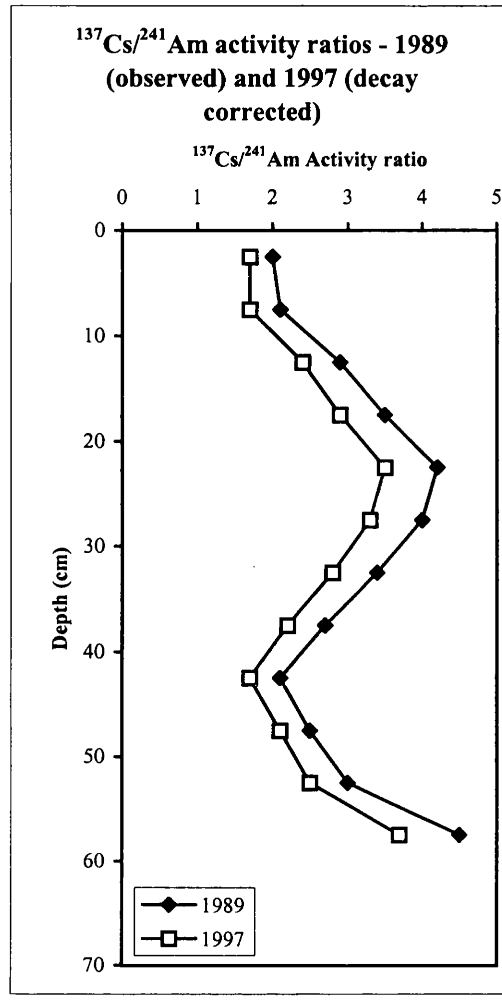


Figure 6.6 Decay-corrected and original $^{137}Cs/^{241}Am$ activity ratio profiles for Southwick Merse (1986 and 1989)
(original data from MacKenzie *et al.,* 1994)

Of the 10 cores, six exhibit a peak in $^{137}Cs/^{241}Am$ activity ratios (Figure 6.7). Table 6.18 illustrates the sedimentation rates derived from the peak ratios in these cores. The sedimentation rates were calculated using 1981 as the earliest time from which peak ratios would have accumulated on the marsh. In all cases, the central point of peak activity ratios was used rather than the highest ratio value. The $^{137}Cs/^{241}Am$ activity ratio peaks are very well defined compared to those at Southwick which may be an artefact of the sampling strategy or a function of the sediment dynamics on the saltmarsh.

Core	Peak $^{137}Cs/^{241}Am$ activity ratio - midpoint depth (cm)	Sedimentation rate (cm y^{-1})
ORB	75	4.7
ORF	22.5	1.4
ORG	20	1.25
ORH	21	1.3
ORJ	54	3.4
ORK	31	1.9

Table 6.18 Sedimentation rates for Orchardton cores utilising $^{137}Cs/^{241}Am$ activity ratios

The sedimentation rates determined from the $^{137}Cs/^{241}Am$ activity ratios are consistent with the pattern of sedimentation discussed above. The highest rate is attributed to the pioneer *Salicornia* marsh, Core ORB, with lower rates present on the *Spartina* marsh. In addition, the highest rates on the *Spartina* marsh are located at the landward side of the study area, Cores ORJ and ORK. These cores were both excavated from areas colonised by species other than *Spartina,* which appear to facilitate sedimentation. As with the rates determined using the radionuclide specific activities, Core ORJ has a higher rate than the other marsh areas.

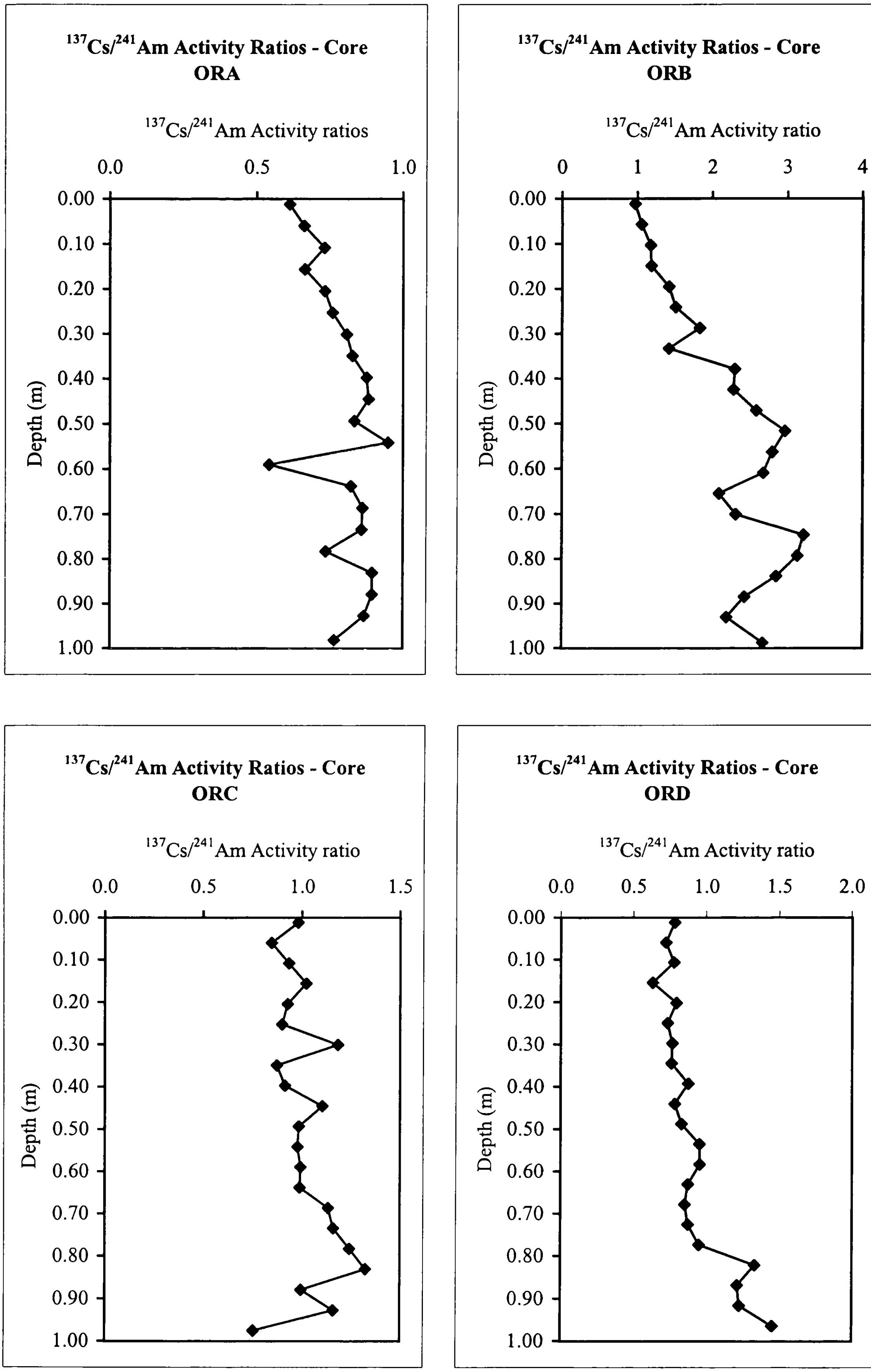


Figure 6.7 $^{137}Cs/^{241}Am$ Activity ratio profiles - Cores ORA, ORB, ORC, ORD

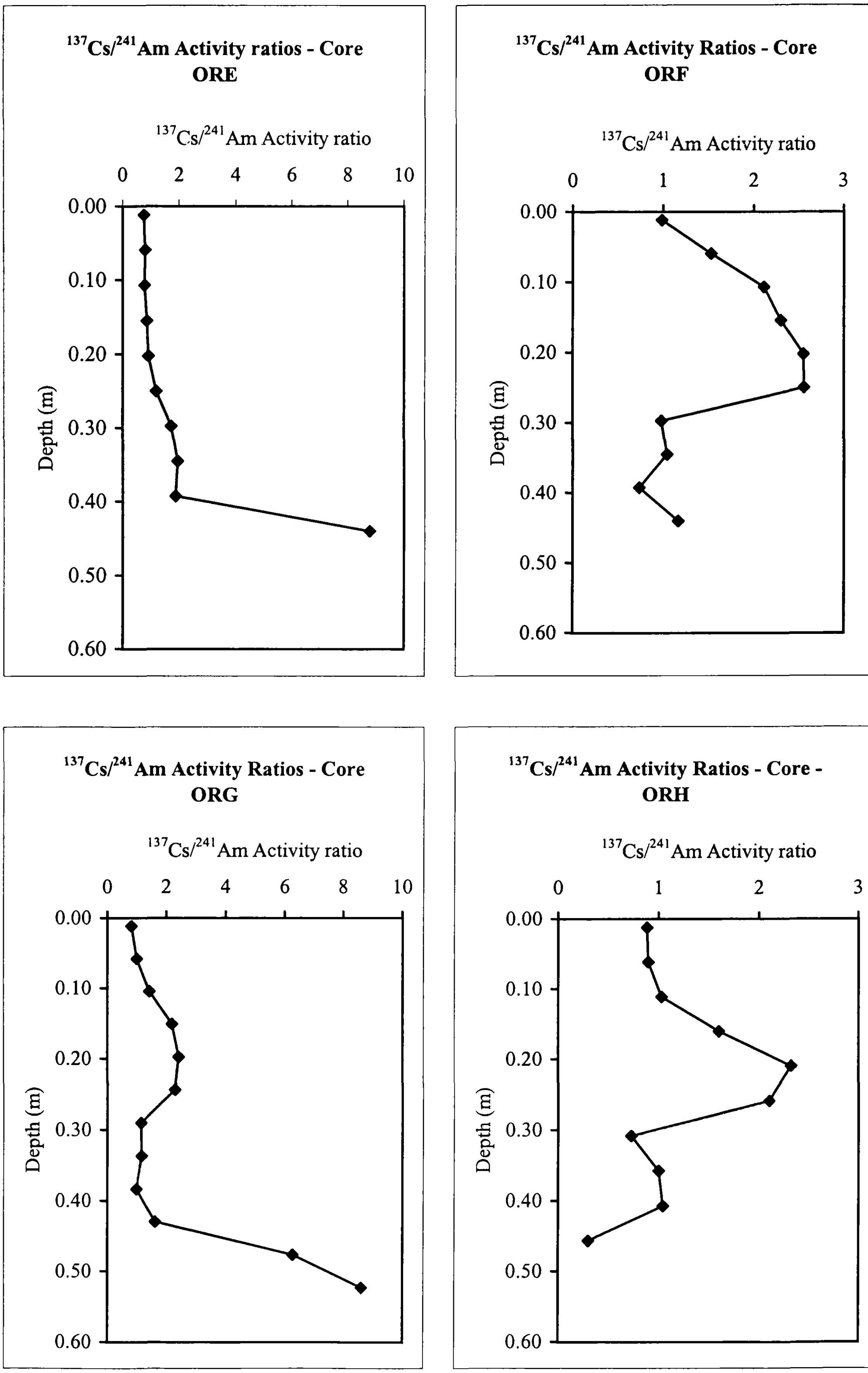
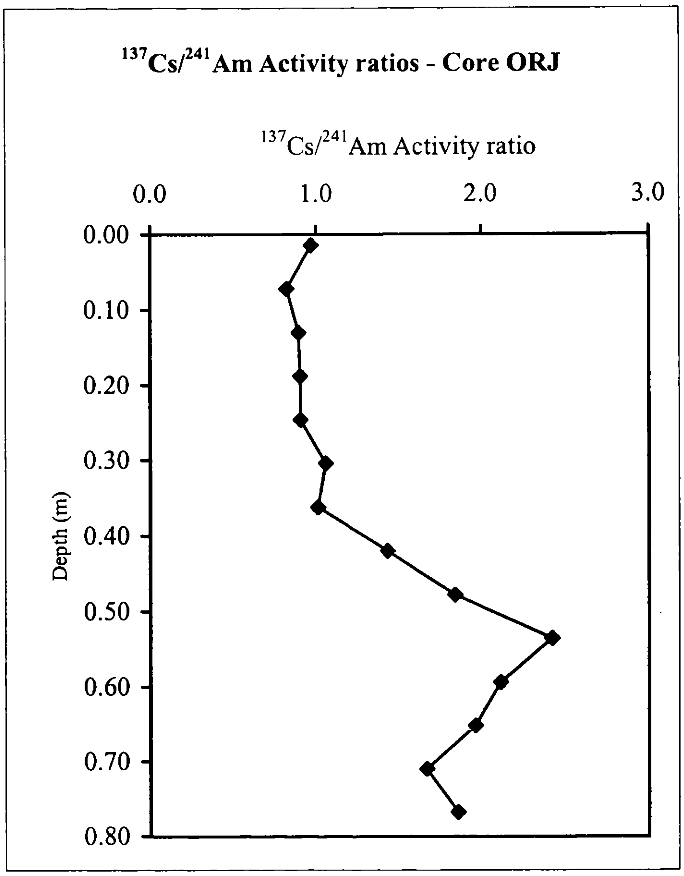


Figure 6.7 (cont.) $^{137}Cs/^{241}Am$ Activity ratio profiles - Cores ORE, ORF, ORG, ORH



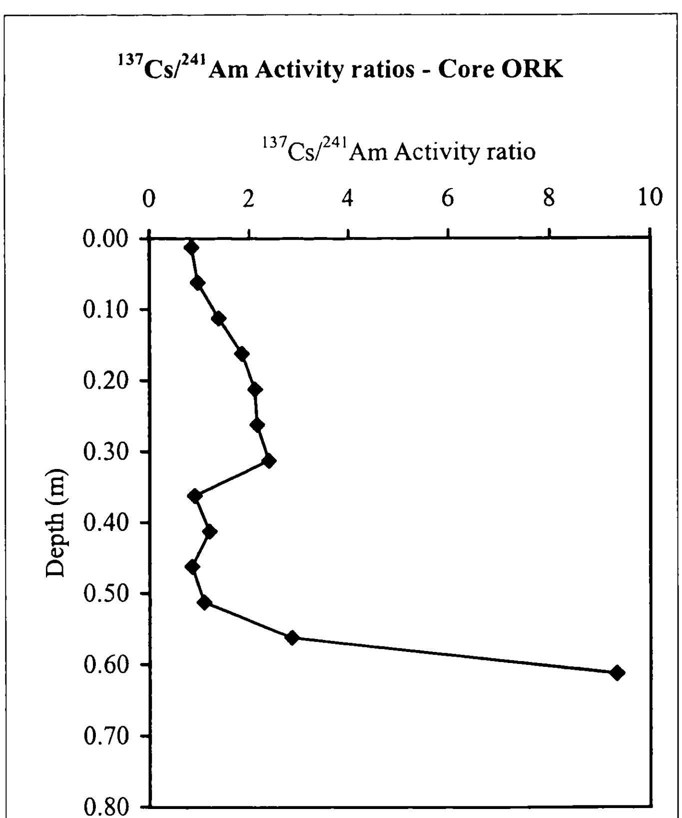


Figure 6.7 (cont.) $^{137}Cs/^{241}Am$ Activity ratio profiles - Cores ORJ, ORK

The three sets of sedimentation rate data can be compared to establish the manner in which sedimentation on Orchardton marsh has developed over time. The graphs in Figure 6.8 illustrate that there is a decrease in sedimentation rates over time over the whole marsh and that this reduction is linear in nature, although the strength of the linearity is less than those derived for Southwick. In Cores ORF, ORG and ORH the rates established using the activity ratios are similar to those derived from the specific activity maxima rather than being lower and it is this which has reduced the strength of the curve. In these three cases, it would appear that contemporary sedimentation rates have decreased dramatically in recent times whilst historic rates were maintained at higher levels. In Cores ORJ and ORK, the sedimentation rates established from the $^{137}Cs/^{241}Am$ activity ratios are higher than those from the analysis of the radionuclide specific activities indicating an increase in sedimentation rates over time. Whilst this appears unusual in terms of the expected pattern of marsh development, an explanation for these patterns may lie in the development of Orchardton. The area covered by Orchardton marsh expanded rapidly after planting of *Spartina* in 1951 (Pye and French, 1993). It can be assumed that in addition to lateral expansion, vertical accretion would also have occurred and, given the rapid colonisation of *Spartina* after the initial planting, this vertical accretion may also have been rapid. This growth may have been self limiting because waterlogging stresses begin to affect the growth rates and stem densities of the *Spartina* (Pye and French, 1993). Reduction in these caused a decrease in sedimentation rates.

Core ORJ, does exhibit a slightly different pattern, requiring further explanation. In each of the cores supporting a subsurface maximum, the 'beginning' of the peak occurs close to the marsh surface. In Core ORJ, the activity ratio peak does not become apparent until a depth of 36 cm, resulting in the calculation of a high sedimentation rate from the $^{137}Cs/^{241}Am$ activity ratio. Indeed, if the contemporary rates are discarded, there is a linear *increase* in the sedimentation rates over time. The ratios within the upper sections of Core ORJ are very similar with a mean of 0.9 +/- 0.09, a value comparable to contemporary Irish Sea surface sediments (MacKenzie *et al.,* 1998). This suggests that sedimentation of this upper section has occurred quickly although the proximal plate data (Plate 27) do not support this idea. There are difficulties in explaining this apparent discrepancy.

These trends indicate that some parts of the marsh are already in a state of degradation (Cores ORF, ORG) and that other parts (Cores ORH, ORJ and ORK) are likely to follow suit unless there is a change in the efficiency of the sediment trapping regime of the marsh. The strength of the trends also suggests that this linear rate of sedimentation reduction is not simply a contemporary phenomenon.

Kestner (1975) and Pethick (1981) both suggest that the maximum height of a marsh will reach an asymptote at some distance below the height of the highest tidal level where the frequency of tidal inundation is so low that there is no further accretion of the marsh. French and Spencer (1993) and Hayden *et al.* (1995) state that sedimentation will still occur at high levels during high spring tides and storms but that this accretion may be offset by regional subsidence. These graphs, however, suggest that the mature *Spartina* part of Orchardton Merse may not be accreting sufficiently to maintain marsh height.

Pethick (1981) also suggests that compaction of the marsh sediment, sea level variations and the density of marsh vegetation may impact on the mechanism of marsh development. Kearney *et al* (1994) note that compaction of sediments under their own weight can occur at depths of less than 1 m, particularly in highly organic systems. However, Orchardton sediments are not highly organic and since most of the samples were from a depth of less than 50 cm it is thought unlikely that autocompaction is exerting a major influence. This area is not, according to Shennan (1989), subsiding and may be either static or experiencing a fall in relative sea level. Finally, since the marsh is covered at every spring tide, it is unlikely that Orchardton has reached its maximum height therefore reducing its accretion to an imperceptible amount.

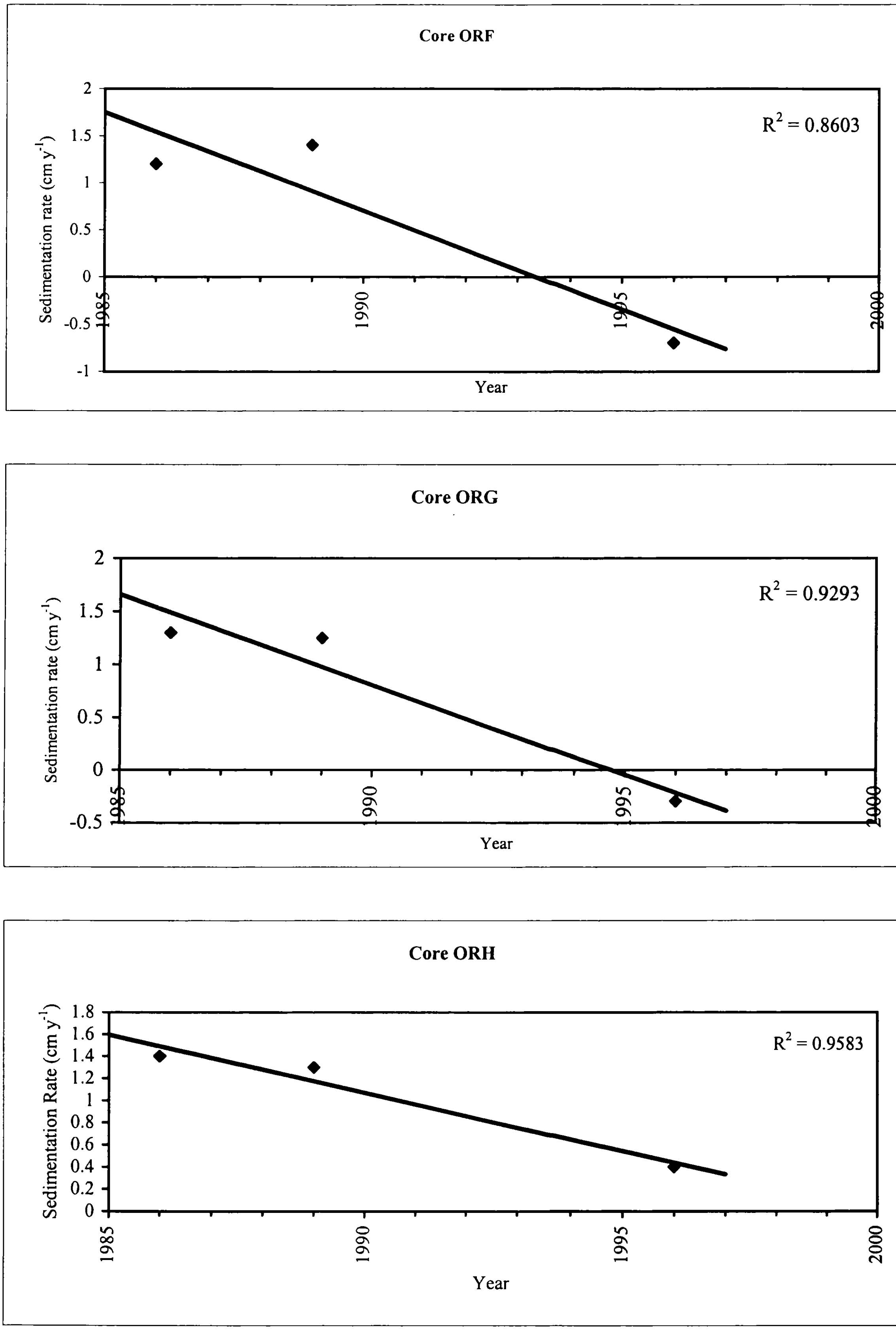
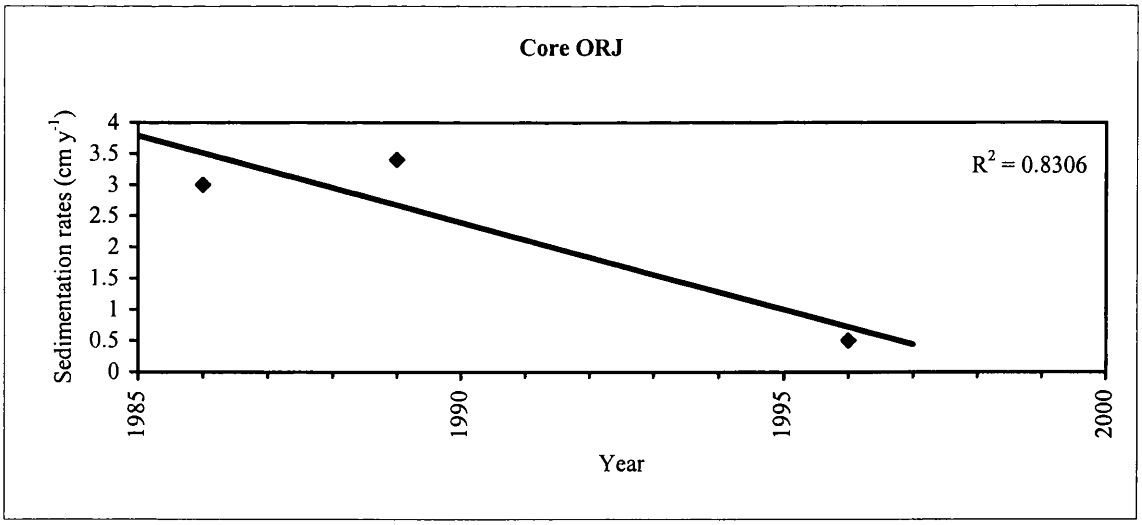


Figure 6.8 Sedimentation rates for Orchardton Merse - Cores ORF, ORG, ORH



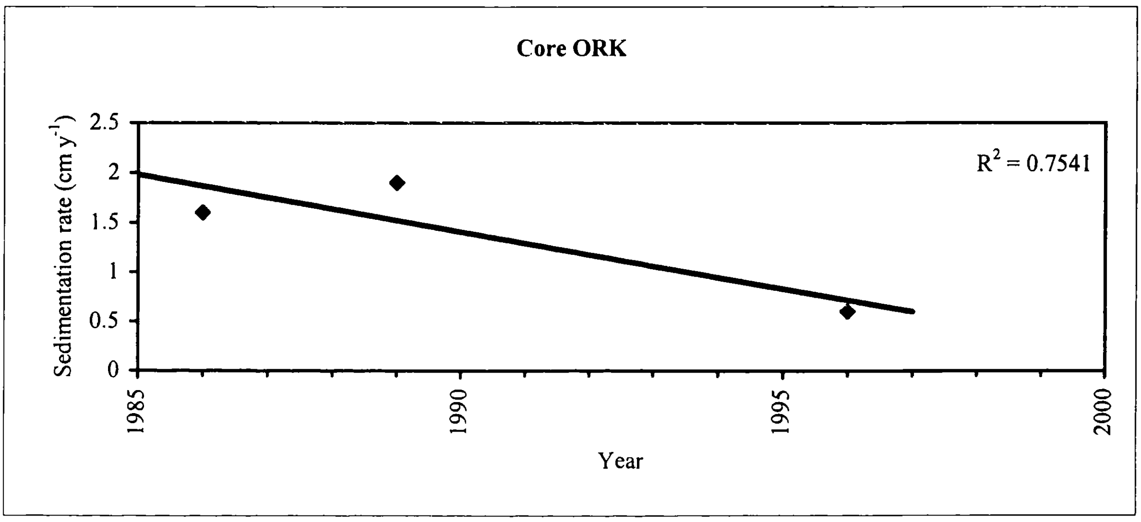


Figure 6.8 (cont.) Sedimentation rates for Orchardton Merse - Cores ORJ, ORK

The density of the marsh vegetation is, undoubtedly low, especially in the lower parts of the marsh and, as has already been discussed in relation to the plate data, may be causing sediment to be resuspended before it can consolidate. Reed and Cahoon (1992) and Nyman *et al.* (1994), working on *Spartina* marshes in the USA, have noted that degradation of the marsh can occur due to waterlogged conditions which causes plant stress due to an accumulation of toxic sulphides. The permanently wet nature of the Orchardton marshes has been commented on and it is possible that marsh degradation may occur at Orchardton. Whilst it is appealing to seek an anthropogenic trigger for this degradation, it is more likely to be related to hydrologic isolation of the system. Insufficient sedimentation results in low areas impounding water and this limits plant production. A reduced vegetation density limits vertical accretion and favours a high hydroperiod and flooding (Nyman *et al.,* 1994). This feedback sequence results in high areas maintaining a positive accretionary status and low areas maintaining low accretion or even erosion. This development of the micro-topographical differences in Orchardton has occurred over the study period (Map 2b).

The core and plate data indicate that the *Spartina* marsh at Orchardton is steadily degrading. Whilst it should be noted that the variations in accretion rates on such a marsh can complicate any assessment of a marsh's ability to keep pace with any potential increases in sea level (Kearney *et al.,* 1994), the evidence from these two sources suggests that Orchardton will be unable to maintain sufficient accretion, even if sea level remains constant in the future, far less if it rises.

6.3.3.2 Interpretation of Orchardton sedimentation patterns utilising $^{137}Cs/^{241}Am$ activity ratios

Interpretation of sedimentation patterns using the $^{137}Cs/^{241}Am$ activity ratios is based on the following observations:

- as a consequence of the loss of ^{137}Cs relative to ^{241}Am due to the processes of radioactive decay and redissolution, there is a systematic decrease in the $^{137}Cs/^{241}Am$ activity ratio through time

- dissolution also results in a decrease in the activity ratio with time, within accumulated sediments peak, therefore peak $^{137}Cs/^{241}Am$ ratios will be in the region of 2.9
- in an accumulating sediment, the $^{137}Cs/^{241}Am$ activity ratio profile will compare to Figure 6.2
- profiles not exhibiting a peak have been subject to sedimentation processes other than simple accretion or, recently deposited
- rapid mixing of sediments will result in the homogenisation of activity ratios
- contemporary $^{137}Cs/^{241}Am$ activity ratios in Irish Sea surface seabed sediments are around 1.

Discussion of the sedimentation patterns at Orchardton will be based around the geomorphological units identified in Section 6.3.1. The $^{137}Cs/^{241}Am$ activity ratio profiles are illustrated in Figure 6.7.

- Mudflat and pioneer marsh – Cores ORA, ORB, ORC, ORD, ORE
- *Spartina* marsh – Cores ORF, ORG, ORH, ORJ, ORK

Mudflat and pioneer marsh

All cores on the mudflat and the pioneer marsh exhibit $^{137}Cs/^{241}Am$ activity ratios increasing in value with depth. The surface ratio values are all 1.0 or less suggesting that the sediment has been recently deposited: an anticipated pattern. Cores ORA and ORD which are both located on the mudflat have very low $^{137}Cs/^{241}Am$ activity ratios. ORA has a mean value of 0.8 +/- 0.12 and ORD has a mean value of 0.8 +/- 0.11 to a depth of 77 cm, below which the activity ratio values increase. These values are exactly what might be expected from sediment recently transported from the Irish Sea. The homogeneous nature of the values indicates that these sediments are subject to intense mixing which may induce a greater degree of redissolution of the ^{137}Cs, thereby reducing the activity ratio.

Cores ORC and ORE have slightly higher $^{137}Cs/^{241}Am$ activity ratio values but neither exhibits a subsurface maximum, again indicating rapid deposition of sediments. There is no apparent reason for the higher activity ratios in these cores, given that they are located on the mudflat and pioneer marsh respectively. Core ORE, located on the pioneer *Spartina* marsh has a very high activity ratio at the base of the core, reflecting higher ^{137}Cs specific activities compared to ^{241}Am. This core provides clear evidence that redissolution of ^{137}Cs is occurring and that ^{137}Cs is undergoing transport and re-deposition. The ^{137}Cs specific activity values are very low compared to all the results which have been discussed thus far and the ^{241}Am specific activity is below detectable limits. It therefore seems that the sediment at the base of Core ORE has not been directly contaminated by Sellafield waste radionuclides but is receiving ^{137}Cs from upper layers of sediments.

Core ORB displays a very different $^{137}Cs/^{241}Am$ activity ratio profile compared to the other cores located on the immature parts of the marsh. This core does exhibit a sub surface maximum very similar in nature to the template core from 1986. In addition the value of the peak is comparable, indeed slightly higher than predicted from the template cores. This suggests that this part of Orchardton has been stable, with a net accretion over a 20 year period in the same manner as accretion at Southwick. This is surprising considering the immature state of the vegetation, comprising only *Salicornia*. This part of the marsh is not covered by every tide but the hydroperiod must be high enough to prevent the colonisation of secondary species.

Spartina *marsh*

All cores excavated from the *Spartina* marsh exhibit a subsurface maximum and higher activity ratios towards the base of the cores. These patterns suggest that sediment has been accreting over the time period of high Sellafield discharges and also that ^{137}Cs is undergoing redissolution in upper layers and being re-deposited deeper in the sediment profile. Of interest is the fact that the peak $^{137}Cs/^{241}Am$ activity ratios in all these cores are lower than the anticipated peak values derived from the Southwick template cores. The highest peak value is evident in Core ORF, a value of 2.6. It is interesting to speculate the reason behind these low values as compared the values demonstrated on the *Salicornia* pioneer marsh and at Southwick. The main difference between these locations and the *Spartina* marsh is the type of vegetation present and the moisture content. The *Salicornia* pioneer marsh and Southwick are well drained with little standing water whereas the *Spartina* marsh at Orchardton is continuously wet. It therefore seems that the waterlogged nature of Orchardton marsh may induce more extensive redissolution of ^{137}Cs which then moves through the sediment. ^{241}Am does not behave in this way, which is unsurprising given its higher K_D value (e.g. MacKenzie *et al.*, 1994, 1998).

6.3.4 Analysis of patterns in $^{137}Cs/^{241}Am$ activity ratio data

The most significant pattern exhibited in the $^{137}Cs/^{241}Am$ activity ratio profiles is the increase in values at depth which indicate that significant re-dissolution of ^{137}Cs is occurring in the sediment profile after which the ^{137}Cs is then transported and re-deposited at depth. This can be explained with reference to the model presented in Figure 6.5.

In some of the cores, ^{137}Cs is detected with no corresponding ^{241}Am, perhaps indicating that the extent of re-dissolution in this marsh is greater than that in Southwick which may be a consequence of the longer residence time of the percolating water due to the waterlogged status of the marsh.

6.3.5 Radionuclide inventories

The ^{137}Cs and ^{241}Am inventories can be assessed in relation to different geomorphic units on the saltmarsh (Table 6.19).

The mudflat areas (Cores ORA, ORC, ORD and ORE) have the lowest inventories reflecting the lack of an activity peak in the sediment profile. The highest inventories are associated with areas of the *Spartina* marsh which are also vegetated with *Puccinellia* and other secondary species (Cores ORJ and ORK).

Comparison of these inventories with those calculated by Allan (1993) demonstrates a large discrepancy in the values for Orchardton marsh (Table 6.20) with those by Allan being significantly higher in some areas and lower in others. This serves to demonstrate that account must be made of the sedimentary environment in interpreting these results.

Core	Depth of analysis (cm)	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})
ORA	98	59 086	75 547
ORB	99	212 246	95 745
ORC	98	88 827	87 594
ORD	96	82 187	90 060
ORE	58	62 107	49 702
ORF	54	117 455	71 571
ORG	66	91 531	54 513
ORH	60	98 330	74 513
ORJ	98	140 318	92 167
ORK	66	131 594	88 668

Table 6.19 Calculated inventories for Orchardton Merse cores

Distance (m) from Mean High Water level*	0 – 15 cm of core		15 – 30 cm of core		Total inventory in top 30 cm of saltmarsh sediments	
	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})
-10	38 025	BDL	59 933	2 146	97 958	2 146
0	1 360	BDL	538	BDL	1 898	BDL
20	202 100	91 591	439 416	185 267	641 516	276 858
40	475 641	178 543	296 833	139 012	772 474	317 555
60	528 865	193 024	240 169	134 792	769 034	327 816
80	396 235	135 365	426 888	225 432	823 123	360 797
100	803 954	320 917	245 491	128 082	1 049 445	448 999
120	724 956	267 044	610 288	223 501	1 335 244	490 545
180	278 848	80 512	18 243	5 869	297 091	86 381
* Positive numbers indicate a movement landward BDL – Below Detection Limit						

Table 6.20 Inventories for Orchardton Merse calculated by Allan (1993)

6.4 Caerlaverock

6.4.1 Eroding site

6.4.1.1 Sedimentation rates and patterns of eroding site derived from plate results

The sedimentation rates experienced on the eroding part of Caerlaverock are extremely variable. The highest sedimentation rates are found on the mudflat and yet these areas also experience dramatic erosion.

The high marsh areas show very similar accretion rates indicating that they are subject to similar periods of tidal inundation. The highest rate is indicated by Plate 6 which is located on the edge of a small pan. This area will be inundated by the tide but because the pan has no outlet, the tidal water will be unable to escape, thereby allowing full settling of sediment carried in suspension. Plates 1 and 4 are located furthest inland and have the lowest of the rates demonstrated on the high marsh; 1.6 cm y^{-1} and 2.2 cm y^{-1}, respectively. At a similar distance inland, but located on the edge of a large pan, are Plates 2 and 3 which indicated rates of 2.6 cm y^{-1} and 2.4 cm y^{-1}. These results indicate that proximity to pans induces higher sedimentation rates. The similarity in the rates of Plates 2 and 3 is to be expected because they are subject to similar amounts of inundation.

This pattern is also shown by plates located closer to the front edge of the marsh. For example Plates 20 and 8 are both 8 m from the marsh edge with the former also located close to the edge of a pan. The rates of these plates are 3.0 cm y^{-1} and 2.7 cm y^{-1} respectively.

The results show that progressively higher sedimentation rates are also exhibited in plates located nearer to the front of the marsh, illustrating that these areas are inundated more frequently. At more exposed points along the edge of the marsh, erosion by waves may also occur, which may account for the slightly lower sedimentation rate indicated by Plate 14.

The only other areas of sedimentation are on the mudflat, where, as with the other study sites, the greatest accretion rates are shown. Indeed, as mentioned in Chapter Five, Plates 17 and 19 gave only one set of measurements because the plates could not be relocated for a second set, probably because the plates were buried too deeply for the measuring spike.

The most dramatic aspect of the sedimentation pattern at this site, is the extensive frontal erosion of the marsh. Almost all of the plates positioned on the edge of the marsh were eroded away during the course of the study. The erosion occurs by way of a two fold process. Firstly, the vegetation turf is stripped from the marsh surface, indicated by rapid erosion rates (demonstrated by Plate 9). The exposed marsh surface is then progressively eroded by successive tides and wave activity. This second component of the erosion process is illustrated in Plates 6.2 and 6.3: Plate 6.2 shows the marsh edge prior to inundation by the tide with 6.3 illustrating the tide moving across the exposed marsh surface.

Plate 6.2 Marsh edge at Caerlaverock illustrating exposed sediment due to turf stripping

Plate 6.3 Tidal inundation of the exposed marsh surface at Caerlaverock

There is a significant amount of erosion occurring at the front of this part of Caerlaverock marsh but, despite this, there is also vertical sedimentation of the marsh surface. The incidence of waves at this location is almost normal to the marsh edge which would account for the severity of the erosion through the process of turf stripping. Once the vegetation has been removed from the marsh, the rate of erosion slows both vertically and laterally. There is no clear evidence for the reason behind the continued erosion of this part of the marsh. Rowe (1978) suggests that erosion on the western side of the marsh has resulted from eastwards movement of the River Nith, whilst Marshall (1960-61) that erosion is driven by the build-up of storm waves by prevailing south-westerlies. It is tempting to postulate that further erosion is likely in response to increased stormy conditions resulting from climatic change.

The greatest amount of sedimentation is occurring on the mudflat and on those areas of the high marsh which are distant from locations of wave impact at the front of the marsh. It is likely that accretion of the mudflat is facilitated by the frontal erosion of the marsh providing a source of sediment. It is also evident that accretion of the mudflat is enhanced by the deposition of sediment around blocks of vegetation, eroded from the front of the marsh.

Sedimentation rates are also higher in areas close to saltpans although it is not clear why this should be.

6.4.1.2 Sedimentation pattern revealed by loss on ignition data

The analysis of the organic content of samples excavated from Caerlaverock marsh (section 5.3.4) showed a distinctive peak, evident in several of the cores. The organic content in the cores above the aforementioned peak is generally very low with little variation.

The position of this peak in the profile (Figure 5.9) varies depending on the position of the core on the marsh. The peak is located at shallow depths in those cores positioned furthest inland. For example, Cores CLE and CLK, both located approximately 40 m from the marsh edge, exhibit the peak at depths around 30 cm. Cores CLD and CLJ, both located 20 m from the marsh edge, demonstrate the peak at a depth of 50 cm. The position of the organic content peak within the cores can be related to the sedimentation rates on the marsh – higher rates exist towards the front edge of the marsh, therefore the organic peak is located deeper in the sediment profile. It can therefore be assumed that the peaks shown in the cores are demonstration of a single event which affected this part of the marsh. An attempt can be made to date when such an event occurred utilising contemporary sedimentation rates. For locations proximal to Cores CLD and CLE, sedimentation rates of 3 cm y^{-1} and 1.6 cm y^{-1} have been determined (Plates 5 and 1 respectively). It can therefore be calculated that the event resulting in the organic peak occurred around 1981/82.

These patterns can be interpreted with reference to the method of erosion highlighted in section 6.4.1. It is suggested that the peak in organic content relates to an eroded surface which has been stripped of vegetation leaving a mass of roots, which has subsequently been covered by further accretion. This hypothesis can be substantiated with reference to

Core CLB located at the front of the marsh which, although is devoid of turf, has a very high organic content in the top 10 cm of the core.

Alternatively, the elevated organic content could have resulted from the marsh surface being buried by an influx of sediment. Whatever the explanation, this pattern demonstrates the highly dynamic nature of this marsh responding, in a dramatic manner, to some key event occurring in the Solway estuary.

6.4.1.3 Determination of sedimentation patterns utilising radionuclide specific activities

The profiles of radionuclide specific activity in Figure 5.10 can be examined to reveal patterns of sedimentation.

Core ORA located in the mudflat fronting the marsh reveals homogeneous ^{137}Cs and ^{241}Am specific activities to a depth of 40 cm (below this depth there is no detectable ^{241}Am and very low levels of ^{137}Cs). This pattern, consistent with mudflat sediments already examined at Southwick and Orchardton, illustrates that the mudflats are highly dynamic and well mixed.

The other cores examined all reveal a peak in specific activities related to high Sellafield discharges, with the depth of the peak relating to geographic location on the marsh. The peak occurs at the lowest depths in those cores which are located in areas of marsh which experience the greatest tidal inundation and therefore the greatest sedimentation rates. The exception to this is Core CLB which exhibits high specific activities at the surface of the core. As mentioned above, this core is located on the front edge of the marsh where the vegetation turf has been stripped away. The erosion has therefore resulted in high concentrations of radionuclides being exposed in surface sediments, thereby increasing the likely exposure of anyone using this part of the marsh.

6.4.1.4 Determination of sedimentation rates utilising radionuclide specific radionuclide activities

The sedimentation rates of those cores exhibiting peak in radionuclide specific activities can be established, although it must be appreciated that the sampling increment used for this site means that the error margins in the calculation are increased (Table 6.21). These rates compare well to the contemporary rates in that the lowest rate is located furthest inland. The highest rate is located in the middle of the study area next to a small pan. The slightly lower rate exhibited at the front edge of the marsh may be attributed to increased wave energies in this location (compare with low sedimentation rates exhibited by Plate 14, also located close to the marsh edge).

Core	Depth of ^{137}Cs maxima (cm)	Sedimentation rate (cm y^{-1})
CLC	47	2.3
CLD	56	2.8
CLE	22	1.1

Table 6.21 Calculated sedimentation rates for Caerlaverock cores

Although the general patterns are consistent with contemporary rates, the actual rates are higher than those rates determined by corresponding sedimentation plates. This is unlike Southwick and Orchardton which both exhibit reducing sedimentation rates over time.

The erosion of the marsh edge may provide an explanation for this pattern. In many marshes, an increase in marsh height coupled with a prograding marsh edge, results in any one area of marsh 'moving' progressively landward. This results in a reduction in tidal inundation and therefore accretion. However, at this location, areas which are currently near the front edge of the marsh would have, in the past, been located further inland meaning they will now be more frequently inundated. This will result in an increase in sedimentation rates over time until inundation is limited by the height of the marsh.

6.4.1.5 Determination of sedimentation patterns utilising $^{137}Cs/^{241}Am$ activity ratios

The patterns of sedimentation can also be investigated with reference to the ^{137}Cs/^{241}Am activity ratios (see 6.2.3 for background information). As with Southwick and Orchardton these activities must be compared to a template illustrating the changes which have occurred in the Sellafield activity ratios over time. The Southwick templates from 1986 and 1989 (Ben Shaban, 1989; Allan, 1993) are again used with the appropriate decay correction (Figure 6. 9). The activity ratios for the analysed cores are given in Figure 6.10.

Interpretation of sedimentation patterns using the ^{137}Cs/^{241}Am activity ratios is based on the following:

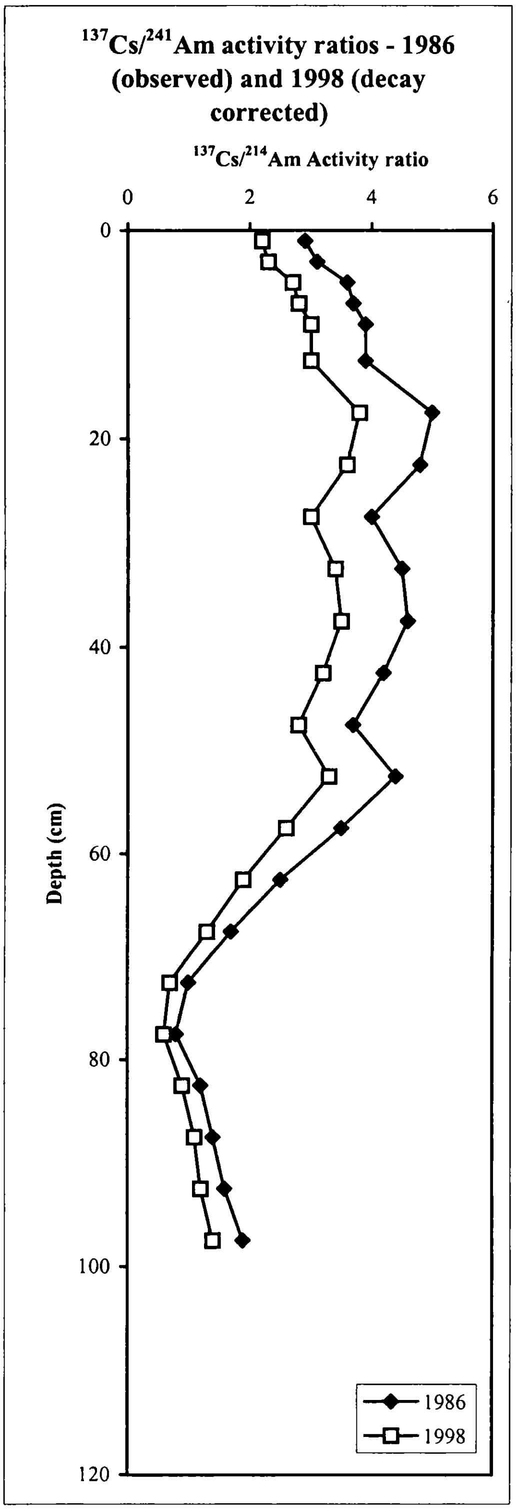
- as a consequence of the loss of ^{137}Cs relative to ^{241}Am due to the processes of radioactive decay and redissolution, there is a systematic decrease in the ^{137}Cs/^{241}Am activity ratio through time

- dissolution also results in a decrease in the activity ratio with time within accumulated sediments, therefore peak ^{137}Cs/^{241}Am ratios will be in the region of 2.9

- in an accumulating sediment, the ^{137}Cs/^{241}Am ratio will compare to Figure 6.9

- profiles not exhibiting a peak have been subject to sedimentation processes other than accretion or, recently deposited

- contemporary ^{137}Cs/^{241}Am activity ratios in Irish Sea surface seabed sediments are around 1.



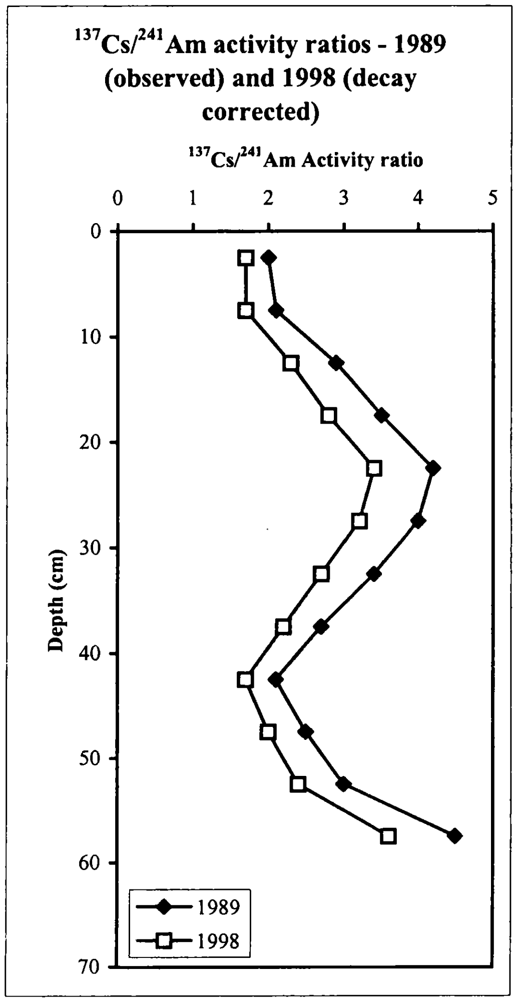


Figure 6.9 Decay-corrected and original $^{137}Cs/^{241}Am$ activity ratio profiles for Southwick merse (1986 and 1989)
(original data from MacKenzie *et al.,* 1994)

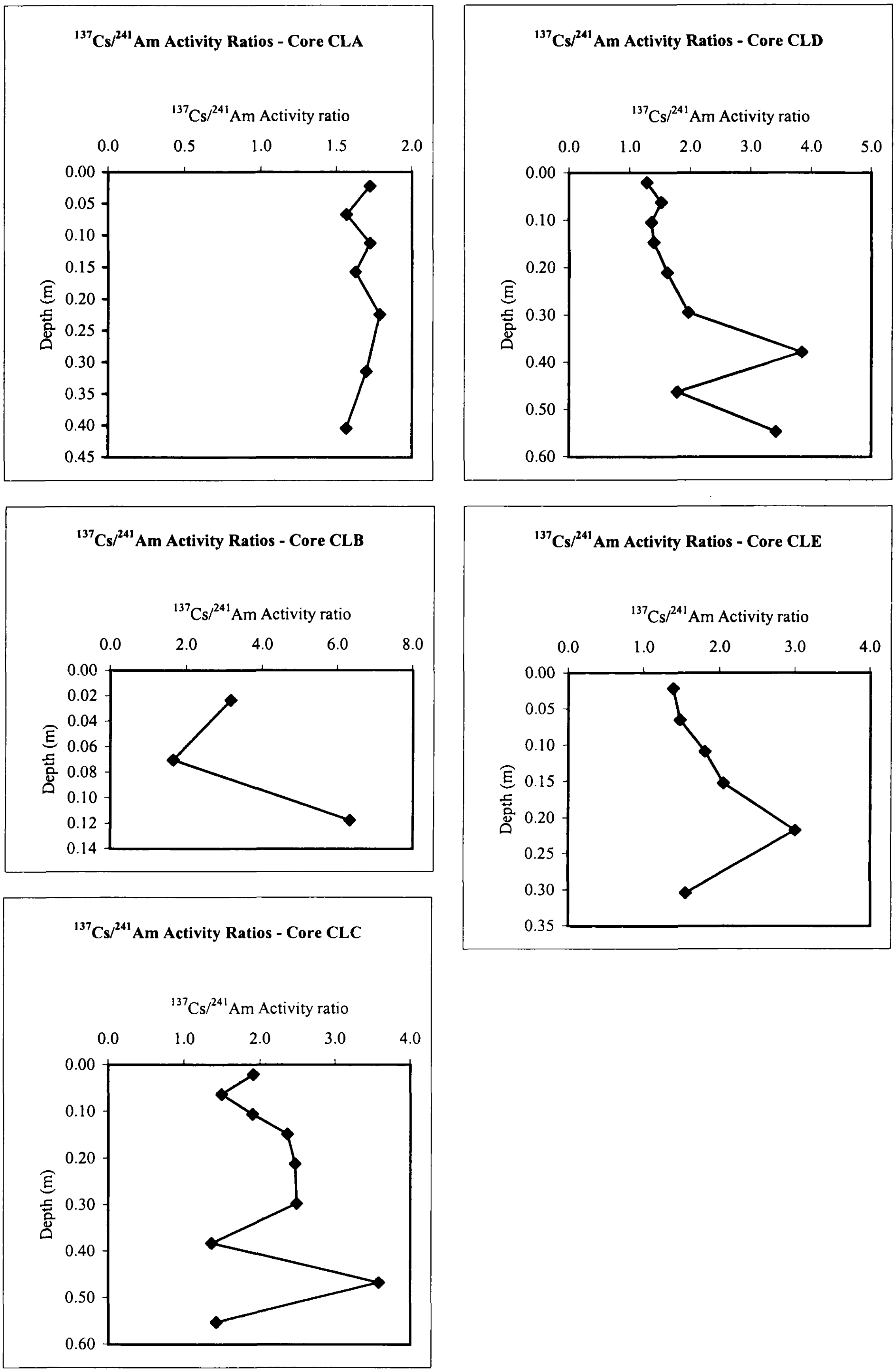


Figure 6.10 $^{137}Cs/^{241}Am$ Activity ratio profiles - Caerlaverock eroding site

In all cases the $^{137}Cs/^{241}Am$ activity ratios exhibited in the upper parts of the cores are higher than expected if we assume that the sediment accumulating on the marsh surface has been supplied from an offshore Irish Sea source. In Southwick and Orchardton cores, surface activity ratios rarely exceed 1, whereas in these cores, the activity ratio values are all greater than 1 and, indeed, in Cores CLB and CLC are 3.2 and 1.9 respectively. Although the specific activities associated with these ratios are relatively low, they are not low enough to assume that the high ratios are a consequence of ^{137}Cs redissolution (as in previous interpretations for Southwick and Orchardton). This suggests that the sediment accumulating on the surface has come from a source of sediment contaminated by Sellafield discharge at a time of higher ratios. This clearly indicates that sediment is being recycled from either another marsh, or more likely, from the eroding edge of Caerlaverock.

The high surface $^{137}Cs/^{241}Am$ activity ratio in Core CLB, located on the eroded edge of the marsh, is due to the Sellafield peak activities being exposed at the surface because of erosion. The profiles for Cores CLB and CLD and the data for the other cores (Appendix 3, Table iii) all indicate elevated ^{137}Cs specific activities at depth again indicating re dissolution and transport.

These results indicate that the pattern of radionuclide distributions are dependent on the geomorphology of the accumulating sediment. Movement of radionuclides, both ^{137}Cs and ^{241}Am can occur as a consequence of physical processes with ^{137}Cs also being transported through chemical processes.

6.4.1.6 Radionuclide inventories

The inventories calculated for the eroding site of Caerlaverock are presented in Table 6.21. These inventories are significantly lower than those established for Southwick and Orchardton. Allan (1993) suggested that there was a reduction in inventories towards the inner Solway Firth because of increasing distance from Sellafield, however, it is tempting to suggest that in the case of Caerlaverock, the lower inventories result from sediment contaminated with high radionuclide concentrations having been previously eroded from the saltmarsh. The current source of sediment for the accretion of this marsh is from both sediment recycled from the eroded edge of the marsh and from Irish Sea sediments which have low levels of contamination.

Core	Depth of analysis (cm)	^{137}Cs (Bq m^{-2})	^{241}Am (Bq m^{-2})
CLA	58	16 481	9 801
CLB	24	30 974	8 705
CLC	64	36 978	16 541
CLD	72	31 690	15 388
CLE	39	24 712	12 326

Table 6.22 Calculated inventories for Caerlaverock Merse cores – eroding site

6.4.2 Accreting site

6.4.2.1 Sedimentation rates and patterns of accreting site derived from plate results

As a consequence of frequent tidal inundation of all parts to this site, sedimentation rates are uniformly high. The lowest rates are found at the landward most parts of the saltmarsh resulting from a lower hydroperiod.

Highest sedimentation rates are associated with mudflat areas rather than the vegetated pioneer marsh, which is perhaps surprising given the increased sediment trapping capabilities of pioneer vegetation. However, the mudflat fronting this marsh is very extensive which may result in waves being largely attenuated before they reach the areas of vegetation. Indeed the immaturity of this part of Caerlaverock Merse will see sedimentation occurring on random undulations on the saltmarsh surface rather than associated with vegetation.

The relationship between the height of the marsh and colonisation of vegetation can vividly detailed on this site as shown in Plate 6.4. Increases in height through sedimentation result in firstly the introduction of pioneer *Puccinellia* and subsequently colonisation by secondary species such as *Ameria and Triglochin.*

Plate 6.4 Vegetation succession on pioneer saltmarsh

6.4.2.2 Sedimentation patterns revealed by loss on ignition data

As with the discussion of the eroding site at Caerlaverock, the organic content profiles (Figure 5.11) reveal that periods of erosion have punctuated the development of this site.

Cores CKJ and CKK, both located on well vegetated high marsh, have profiles very similar to those identified at Southwick Merse which suggests that perhaps the mode of sedimentation occurring on these high marsh areas is similar to that at Southwick, i.e. organic rich layers of sediment being deposited as a consequence of vegetation being flattened by the incoming tide.

Core CKF has a high organic content near the top of the core but yet is located on low marsh, which other cores in similar locations, e.g. Core CKE, show to have relatively low organic levels. In Chapter Five it was indicated that erosion has occurred on this part of Caerlaverock, revealed by the existence of a small cliff separating the high and low marsh. The high organic content in Core CKF suggests that this area was once covered by more heavily vegetated marsh but that this has been eroded, perhaps by the same method as outlined in discussion of the eroding part of Caerlaverock.

6.4.2.3 Determination of sedimentation patterns utilising radionuclide specific activities

The profiles of radionuclide specific activity (Figure 5.12) indicate that while the activities for both ^{137}Cs and ^{241}Am are low, they occur to depths of at least 60 cm in the analysed cores. Peak activities of ^{137}Cs are remarkably consistent in each core at between 300 Bq kg^{-1} and 400 Bq kg^{-1}. ^{241}Am activities do not exceed 100 Bq kg^{-1}. These results indicate that accretion of this site has occurred with sediment coming from a source which has had either limited contact with the Sellafield discharge or has been greatly diluted.

6.4.2.4 Determination of sedimentation patterns utilising $^{137}Cs/^{241}Am$ activity ratios

Profiles of $^{137}Cs/^{241}Am$ activity ratios for cores excavated from this site are presented in Figure 6.11. The activity ratios clearly indicate that the sediment accumulating on this new area of marsh is derived from a source which was contaminated with Sellafield discharge at a time when activities were much higher. This contaminated sediment has become diluted such that the specific activities on the marsh are very low. Cores CKB and CKC have no detectable ^{137}Cs or ^{241}Am in their surface sediments indicating the extent of the dilution.

In addition to this, it should be noted that the ^{137}Cs levels are much higher than the corresponding ^{241}Am values, which suggests that movement of ^{137}Cs is occurring through the sediment profile, a situation exemplified in Cores CKC and CKD.

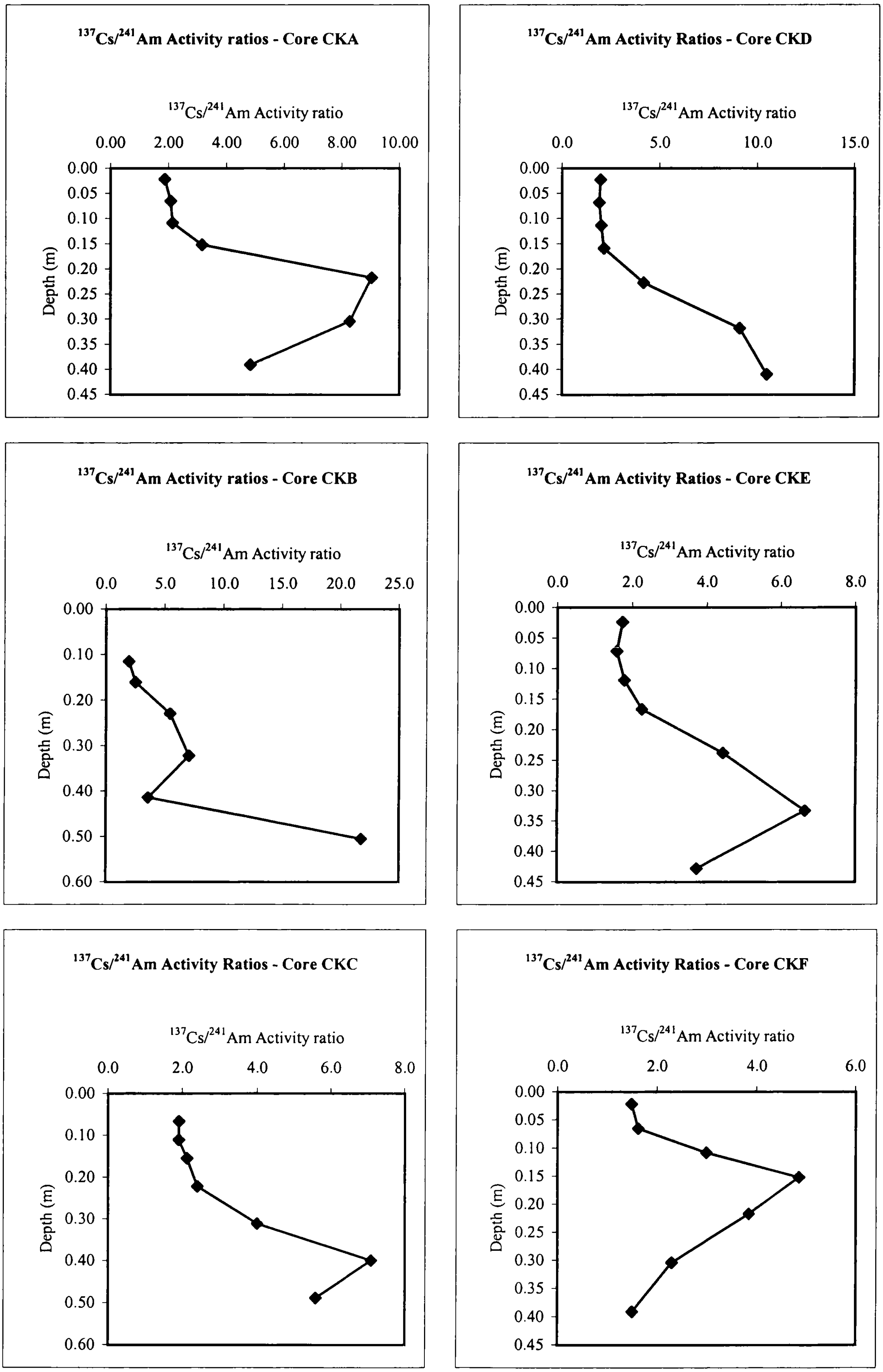


Figure 6.11 $^{137}Cs/^{241}Am$ Activity ratio profiles - Caerlaverock accreting site

6.4.2.5 Radionuclide inventories

Although the radionuclide specific activity levels are low compared to other sites, including the eroding site on Caerlaverock, the inventories are comparable to this latter site. The reason for this is that the saltmarsh is being created and maintained by sediment which has been contaminated with high radionuclide concentrations which are now diluted.

Core	Depth of analysis (cm)	^{137}Cs ($Bq\ m^{-2}$)	^{241}Am ($Bq\ m^{-2}$)
CKA	57	31 531	5 765
CKB	60	29 423	6 342
CKC	58	29 225	7 674
CKD	41	27 038	5 964
CKE	52	38 031	10 795
CKF	57	32 087	11 534

Table 6.23 Calculated inventories for Caerlaverock Merse cores– accreting site

7 INTER-MARSH COMPARISONS

7.1 Introduction

An original premise of this work is that although the Solway Firth can be regarded as an integrated whole, there exists within the estuary a large degree of variability and this is reflected in the physical form of saltmarshes. Chapter three proposed that the marshes within the Solway can be classified according to their physiographic location, vegetation and landuse and that this results in a broader classification system than the 'estuarine' characterisation often used in the literature. Chapter two indicated that only a few studies have investigated marshes in different physiographic locations. This is because of the dominant influence of tidal conditions in determining the sedimentary regime of the marsh, a phenomenon which will change significantly between estuaries. The Solway marshes however, are largely affected by similar tidal conditions (because they are located within the same estuary), thereby making a comparative study feasible. One of the aims of this project was to *investigate the influence of physiographic location on saltmarsh development* (from p. 66).

The previous chapter analysed the study sites on an individual basis and suggested that fundamental differences exist in saltmarsh development that impact on the distribution of radionuclides within the saltmarshes. However, as saltmarsh development is significantly controlled by tidal conditions, are there comparisons to be made in saltmarsh development across the estuary as a whole? By comparing these different marshes, controls of saltmarsh development operating on an estuary wide scale, can be elucidated.

This chapter will therefore examine the extent of variation *and similarity* between saltmarshes within the Solway Firth.

7.2 Sedimentation rates and patterns

7.2.1 Sedimentation rates and patterns: the expected pattern

In general terms, sedimentation on saltmarshes is controlled by hydroperiod: the greater the inundation a saltmarsh experiences, the higher the sedimentation rate. Through time the hydroperiod will reduce as a consequence of increased elevation. In the shorter term, sedimentation patterns will be driven by proximity to the source of tidal waters: this may be tidal creeks (e.g. French, 1993) or may result from overflow of the seaward edge of the marsh (Pethick, 1984). This means that there are generally higher sedimentation rates towards the seaward edge of the marsh and adjacent to tidal creeks. The lowest sedimentation rates will be at the landward edges of the marsh, areas which will only be inundated during high spring tides or storm conditions.

The pattern of vegetation colonisation mirrors the accretion pattern in that increases in elevation will result in fewer halophytic species being present on elevated parts of the marsh. Substantial colonisation of the saltmarsh will occur once the marsh elevation has reached the level of the Mean High Water Neap (e.g. Long and Mason, 1983). Once vegetation is established, there will be a rapid increase in sedimentation resulting from the capacity of vegetation to trap sediment. Tidally dominant marshes, such as those in the Solway Firth, accrete via inorganic sedimentation although there will be some organic sedimentation resulting from vegetation decay (this may result from the seasonal die back of annual species).

7.2.2 Sedimentation rates and patterns: spatial pattern in the Solway Firth saltmarshes

On the whole, the above pattern of sedimentation was reflected at all four study sites. The sedimentation rates experienced on the mudflats are generally very variable exhibiting high rates of sediment accretion and erosion. The mudflat is subject to very frequent inundation by the tide, and is affected by meteorological conditions and wave activity, all of which results in the movement of sediment. Stability only occurs when vegetation begins to become established.

The highest rates of sedimentation are located at the seaward edge of the saltmarshes and adjacent to tidal creeks, reflecting more frequent inundation by the tide. The lowest rates are located at the landward edge of the marsh. These patterns are exhibited most convincingly at Southwick and Caerlaverock, especially when considered beside the development of vegetation at these sites. These marshes display a general saltmarsh vegetation pattern which conforms to the literature: the type of vegetation present being directly related to the elevation of the site and frequency of tidal inundation. Sedimentation is initiated and enhanced by the development of pioneer species, in this case *Puccinellia,* able to withstand frequent inundation by the tide. As accretion develops, secondary species such as *Salicornia, Aster* and *Ameria* colonise, further increasing the capacity of the marsh to trap and retain sediment.

The pattern of sedimentation at Orchardton is somewhat less consistent with the literature. The most pertinent observation is that the sedimentation rates exhibited at Orchardton, which, when compared to Southwick and Caerlaverock, are a factor of 10 lower than expected. Indeed the rate of sedimentation is now so low that, it is suggested that the marsh surface is currently degrading, caused by a lack of complete vegetation cover and the muddy waterlogged conditions of the soil. Unlike the other sites, the pioneer vegetation at Orchardton is *Spartina,* the development of which was encouraged by planting during the 1950s, and it may be this vegetation type which is now inhibiting sediment accumulation. The *Spartina* on this site does not provide a complete vegetation cover which results in sediment brought in by the tide being re-entrained rather than deposited. Accretion of Orchardton marsh is occurring in those areas, albeit to a small extent, where species such as *Puccinellia* and *Aster* are beginning to colonise.

Degradation of the marsh surface at Orchardton is also attributed to the marsh being continually waterlogged, a phenomenon not experienced on the other study sites. While Southwick and Caerlaverock are inundated by the tide on a regular basis, they drain quickly with the only standing water being contained in saltpans. Indeed in the summer months it is usual to find desiccation cracks in the unvegetated mudflat. Comparison of sediment size data between Southwick and Orchardton does seems to indicate that the latter site has a finer sediment composition which contribute to poor drainage (Figure 7.1). The finer composition of sediment at Orchardton can be attributed to its physiographic location in that the marsh is located at the head of a deeply enclosed bay. Tidal and wave energy levels are very low upon reaching the marsh and result in reduced competence. It is also tempting to attribute the waterlogging to *Spartina* which may not facilitate drainage as effectively as *Puccinellia.* Although this suggestion is speculative, it is substantiated by Gray *et al.* (1990, p. 9) who not that *Spartina* "drastically alters the sedimentary and drainage characteristics of the marshlands and paves the way for its own destruction by the creation of anaerobic soils".

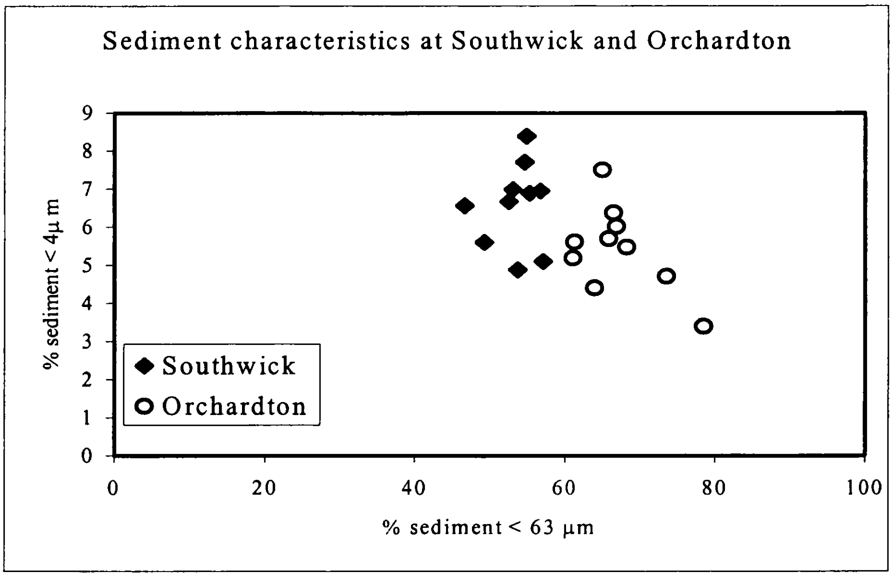


Figure 7.1 Sediment characteristics of Southwick and Orchardton

In order to gain a clearer picture of why Orchardton might have a different sedimentation regime to the other saltmarshes in this study, a comparison of the development of these marshes through time is required.

7.2.3 Sedimentation rates and patterns: temporal pattern in the Solway Firth saltmarshes

As elevation increases on a saltmarsh, the rates of sedimentation will decrease until the elevation reaches an asymptote, thereby precluding further sediment being carried onto the marsh (e.g. Kestner, 1975). It is suggested by French and Spencer (1993) that marsh elevation increases through sedimentation may be offset by regional subsidence and that enhanced sedimentation during high spring tides and storms is important for maintaining the highest parts of the marsh. The temporal history of the Solway saltmarshes can be determined by integrating different methods to establish the marsh's sedimentation pattern. Results from the use of sedimentation plates identified the contemporary sedimentation rates from 1995 to 1997. Historical sedimentation rates were also established using the ^{137}Cs and ^{241}Am activity profiles and the $^{137}Cs/^{241}Am$ activity ratio profiles in cores excavated from the four sites.

The integration of the above methods indicated that at Southwick and Orchardton the sedimentation rate had reduced through time. The results from Orchardton however indicate that the decline in sedimentation rate had occurred rapidly, resulting in the current situation where sedimentation rates are very low or indeed negative. At the Caerlaverock, (eroding site) however, contemporary sedimentation rates appear to be higher than historical rates, suggesting an increase in sedimentation over time. At the Caerlaverock (accreting site) the picture cannot be determined because of a lack of sub-surface maxima in the radionuclide results. The significance of this will be explored later.

These general patterns obscure the fact that the pattern and rates of sedimentation on these sites are complicated by periods of erosion within an overall accretionary regime. This will now be explored.

7.2.3.1 Erosional phases in the Solway Firth saltmarshes

In Chapter six a number of erosional phases were identified associated with the development of Southwick and Caerlaverock and these may inform the present erosion at it Orchardton.

At Southwick, using the radionuclide $^{137}Cs/^{241}Am$ activity ratio profiles and the ^{137}Cs and ^{241}Am activity profiles for cores taken, it was suggested that two phases of erosion have occurred. Interpretation of Core SWB indicated that the front edge of the marsh had been eroded around 1981. Interpretation of cores SWF, SWG, SWH and SWJ indicated that the marsh surface had been stripped away around 1986 and this is supported by geomorphological evidence.

This latter pattern of erosion is mirrored at Caerlaverock (eroding site) where the marsh edge is now being eroded by a process of vegetation stripping, leaving an exposed surface of sediment and vegetation roots. In section *6.4.1.2* it was suggested that this pattern of erosion is not simply a contemporary phenomenon and that a phase of erosion occurred around 1982/1, similarly stripping the marsh of its vegetation. The evidence for this was suggested by a peak in the organic content at depth in the cores. The surface sediments in the areas of current marsh which have been stripped of vegetation have a high organic content due to the decay of the remaining roots.

Therefore, it would appear that an event has occurred in 1981/82 which resulted in the erosion of both Southwick and Caerlaverock.

Examination of the pattern of sedimentation at Southwick shows that the process of surface stripping in 1986 resulted in the surface topography being destroyed, to the extent that there are now no saltpans in the area of affected marsh. Saltpans are however evident higher in the saltmarsh profile in an area which was not affected by this erosional event. In addition to this, examination of Figures 5.2 (Southwick) indicates that the small peaks in the Southwick organic content profiles are roughly coincident with the date of the surface stripping event (Table 7.1). The calculated date for the elevated peaks in Cores SWF and SWH is 1985. For Cores SWG and SWJ the dates are 1988 and 1986 respectively. In interpreting these dates it must be considered that the contemporary sedimentation rate used for SWG is probably elevated because the plate used is near a creek, therefore the date of the higher organic levels may be too recent.

Core	Depth of elevated organic levels (cm)	Associated contemporary sedimentation rate (from plate data) cm y^{-1}	Calculated date of organic peak development
SWF	32	2.6	1985
SWG	46	5.1	1988
SWH	34	2.7	1985
SWJ	22	2.0	1986

Table 7.1 Calculated dates of elevated organic levels in Southwick merse

These observations at Southwick are contrary to patterns at Caerlaverock. The removal of saltpans is not repeated at Caerlaverock, where saltpans are abundant. The peak in the organic profiles of the Caerlaverock cores (Figure 5.9) is very marked and thereby suggests a different process from that at operating at Southwick.

Pringle (1995) noted that low frequency, high magnitude erosional phases were experienced in Morecambe Bay associated with the coincidence of spring tides and strong onshore winds. These generated higher energy waves in both the Irish Sea and Morecambe Bay, which produced rapid rates of marsh edge erosion and deposition of sheets of sandy sediment on the marsh near the eroding cliff, causing vegetation to die the following growing season. Pringle (1995) therefore suggests a mechanism by which a high amount of organic material could be buried within the sediment profile. This interpretation is a more compelling explanation of the organic peak at Caerlaverock. The sediment perhaps being supplied from the estuary as well as erosion of the frontal edge.

What was the nature of the erosional event at Southwick in 1986 which caused the surface sediment stripping as indicated by the radionuclide data? A parallel situation is currently occurring at Caerlaverock where surface stripping is made possible by its exposure to prevailing winds resulting in the incident waves being normal to the marsh edge. The production of this type of wave activity is not possible at Southwick because it is located within a more sheltered location and the marsh in inundated via a large tidal creek.

At Southwick, core SWB suggests that there was a period of frontal erosion at some point after 1981. This erosional episode will have generated sediment that may have been deposited on the marsh surface (as may have occurred at Caerlaverock). The amounts however, were insufficient to completely kill the vegetation (no evidence in the organic content profiles) but may have caused partial die-back of the vegetation. This weakened the structure of the vegetation sufficiently for the vegetation turf and upper sediments to be more easily stripped away in 1985/86.

Comparison of radionuclide data, organic content data and geomorphological evidence across the Solway marshes has indicated that while similar processes of erosion occur across the Solway, the saltmarshes may not respond in the same way to the same event. In 1981 Southwick suffered frontal erosion (evidence from Core SWB) whilst Caerlaverock experienced an influx of sediment which covered and killed its saltmarsh vegetation (evidence from core organic profiles). It is likely that the site also suffered frontal erosion however, evidence for this has yet to be obtained. This illustrates that the marshes will respond to an event which may occur on an estuary wide scale. The method of response may be different in individual cases, but the basic mechanisms operating are similar. It would be interesting to determine if the event which caused erosion in the Solway in 1981, also resulted in similar responses in other marsh systems across the Irish Sea, e.g. Morecambe Bay, Severn Estuary.

Physiographic location appears to have a major bearing on the saltmarsh response to estuary wide events.

7.2.3.2 Interpretation of Orchardton marsh

The above investigation into the development history of Southwick and Caerlaverock and the realisation that estuary wide events impacts all the Solway marshes may offer an explanation to why Orchardton is currently suffering surface degradation.

Events occurred in the Solway Firth in the 1980's which resulted in marshes being eroded: this has been illustrated at both Southwick and Caerlaverock. This would have resulted in a surplus of sediment within the Solway Firth available for accretion in other marshes of the Solway, especially those areas which are very sheltered, such as Orchardton. On this basis, the following scenario is proposed.

In Chapter 6 it was determined that during the 1980s, sedimentation rates at Orchardton increased (Figure 6.8). This pattern of rapid accretion was interpreted as being a consequence of new Spartina planting. However, it also coincident with an increased sediment supply due to erosion of marshes elsewhere and increased energy levels in the Solway which may have facilitated the transport of the sediment to the head of Orchardton Bay. It may also be the case that because of this sediment supply that the continued elevation of *Spartina* marsh was maintained. Eventually the 'extra' supply of sediment would have reduced, resulting in a lowering of the accretion rate such that now, there is insufficient sediment for accretion at Orchardton. The slightly smaller sediment size at Orchardton indicates that the tides rather than waves are more important in carrying sediment in a low competence regime. There is simply not enough sediment now reaching the head of this very enclosed bay.

Although this scenario is speculative, it appears that erosion of exposed saltmarshes is connected in a sediment flux to accretion of more sheltered marshes. Whether this can be substantiated using radionuclide data will be discussed later.

In addition to a reduction in supply, it is possible that Orchardton is also experiencing shallow subsidence resulting from it fine sediment composition. Cahoon *et al* (2000) determined that a *Spartina* marsh at Scolt Head Island in Norfolk experienced shallow subsidence at a rate of nearly 4 mm y^{-1}, which was attributed to compaction of unconsolidated clay sediments. It is possible that Orchardton marsh no longer accretes sufficiently to offset subsidence. The vegetation is now being slowly drowned, reducing the sediment trapping capabilities even further.

This scenario suggests that the saltmarsh at Orchardton has not yet reached an elevation where normal accretionary processes and vegetation succession, such as those at Southwick and Caerlaverock, are possible. This failure would appear to be driven by the nature of the vegetation and a lack of sediment supply, leading to die-back, waterlogging and erosion of inter-vegetation sediments.

The above discussion has demonstrated that although there are differences in the sediment rates and patterns experienced by different marshes on the Solway Firth, they can be explained with reference to the physiographic location of the marshes, and the impact estuary wide events. In addition to this, it has been shown that although the basic mechanisms of development are the same for each marsh, the individual response to an event will vary depending, again, on physiographic location and the type of vegetation present on the marsh.

7.3 Mechanisms of sedimentation

The above discussion, and the discussion in Chapter 6, has suggested that Southwick and Caerlaverock are developing in a different way compared to Orchardton. This difference is reflected not only in the rates and patterns of sedimentation, but in the actual mechanism of sedimentation. These differences are indicated by comparison of the organic content data (loss on ignition) and radionuclide specific activity profiles. Southwick Merse and vegetated parts of Caerlaverock have similar profiles of these data sets, with the main feature being a series of peaks and troughs in values extending the entire length of the core. It is suggested that the peaks in the two data sets are coincident resulting from vegetation being flattened during high tidal influxes, thereby trapping fine grained sediment (with which the highest radionuclide concentrations are associated). This interpretation is supported by the work of Perkins (1966) who noted that sediment deposition was an intermittent process dependant on large tides which transmit sediment further into the Firth.

Orchardton however, does not exhibit peaks and troughs in the organic content data and those which do occur, do not often correspond with a coincident peak in the radionuclide data. It is proposed that sedimentation of radionuclides occurs by a more gradual and systematic method, perhaps by sediment being washed from the leaves and stems of the plants onto the marsh surface as has been shown to occur by Bieniowski (1999) and Stewart (1999). In the latter study it was shown that the washing of sediment from *Spartina* leaves contributed almost 50% of the total sediment input to the marsh and up to 75% high up in the tidal frame. The location of this saltmarsh at the head of a deeply incised bay may also mean that these pulses of sediment cannot reach the head of the bay, further supporting the above idea that sediment supply is an issue at Orchardton.

The coincident patterns between organic content and radionuclide activity levels indicates that there is a close relationship between the development processes of the saltmarsh and the subsequent radionuclide distribution patterns.

7.4 Influence of geomorphology on the distribution of radionuclides

Following on from the above argument it is fair to ask: to what extent does geomorphology control radionuclide distribution?

This study has shown that across the Solway, there is a great degree of variability in both ^{137}Cs and ^{241}Am activities and $^{137}Cs/^{241}Am$ activity ratios. However, the resulting distribution in the radionuclides do conform to a number of consistent patterns. In dynamic parts of the Solway saltmarsh system, such as the mudflats, there is a dilution and homogenisation of the radionuclides within the sediment. These systems are frequently inundated resulting in the rapid movement of sediment, even though they are generally accretionary. This results in low inventories of radionuclides and low $^{137}Cs/^{241}Am$ activity ratios indicating that the sediment within these areas is well mixed with sediment arriving from the Irish Sea carrying a contemporary (i.e. low) contamination by Sellafield discharges. The radionuclide profile in sediments in these areas indicates a general increase in concentration with depth, and reflecting a reduction in Sellafield discharges with time. This pattern is shown at all four study sites.

This pattern might also be expected on rapidly accreting saltmarshes and is demonstrated at Southwick by cores SWD, SWE and SWF.

On marshes which experience a slower accumulation rate such as the middle marsh areas of Southwick and Caerlaverock, it is likely that the ^{137}Cs and ^{241}Am radionuclide activity profiles will bear a qualitative resemblance to Sellafield discharges over the last 30 years. The depth of the peak discharges from the 1970s will be directly determined by the sedimentation rate on that part of the marsh. Therefore, it is to be expected that sub-surface maxima will be at a greater depth at the seaward edge of the marsh and areas adjacent to the tidal creeks. This general pattern is revealed at all the study sites.

In accordance with the literature, there is an increase in the levels of ^{137}Cs and ^{241}Am present on vegetated areas of the saltmarsh compared to the mudflats (e.g. Oldfield *et al.*, 1993), however the results from this study do not indicate that there is a significant difference between radionuclide activities and the type of vegetation present on the marsh. Table 7.2 compares the highest ^{137}Cs and ^{241}Am activities calculated from Southwick and Orchardton cores. This demonstrates that the highest activities are located at Orchardton, although this may be a function of the finer sediment size rather than differences in vegetation.

Cores		Highest ^{137}Cs activities (Bq kg^{-1})	Highest ^{241}Am activities (Bq kg^{-1})
Southwick	SWF	1298	526
	SWG	1655	997
	SWH	1621	762
	SWJ	1870	1154
	SWK	1636	927
Orchardton	ORF	1735	1388
	ORG	1504	794
	ORH	2150	1341
	ORJ	1495	763
	ORK	2323	1626

Table 7.2 Comparison of peak ^{137}Cs and ^{241}Am activities in Southwick and Orchardton saltmarshes

The influence of vegetation on the distribution of radionuclides has already been mentioned in section 7.3, in that there is a greater degree of variability down the core profile in Southwick and Caerlaverock sediments compared to Orchardton, reflecting different sedimentation mechanisms.

In accordance with the observations of Allan (1993) there appears to be easterly decrease in radionuclide concentrations: peak activities are higher at Orchardton compared to Caerlaverock. Garland *et al.* (1988) and Allan (1993) suggest that this is a consequence of increasing distance from Sellafield. The pattern however is not reflected in the radionuclide inventories for the sites with the inventories at Southwick being higher than those at Orchardton or Caerlaverock. The reason for this may provide further evidence that sediment supply has an impact on Orchardton. It is suggested in section *7.2.3.2* that Orchardton, during the 1980s was supplied with increased amounts of sediment. Some of this sediment was derived from material eroded from other saltmarshes, but material would also have been derived from the Solway, entrained due to the higher energy conditions at the time and would have the effect of diluting the radionuclide concentrations reaching Orchardton. Even though the highest activities are found at this site because of a finer sediment composition, the overall inventories may be lower due to dilution effects. In addition to this, it was postulated in section *6.3.3.2* that lower than expected $^{137}Cs/^{241}Am$ activity ratios at Orchardton was a consequence of enhanced redissolution due to waterlogged sediment conditions. However, the above analysis would seem to indicate that a mixing of sediment sources may be another factor. Although this explanation is speculative is does seem to fit with the development history determined for Orchardton. Further investigation is required to validate this theory.

Geomorphology also has an important influence in terms of the redistribution of radionuclides. Saltmarshes are ephemeral systems in the long term and although Mackenzie and Scott (1993) observe that the burial of radionuclide within an accumulating sediment is effective in reducing the external exposure to those using the saltmarshes, these radionuclides may ultimately be redelivered back in to the tidal environment if erosion occurs. This may result in two scenarios, both experienced in the Solway Firth:

- the radionuclides are transported to another marsh;
- higher concentrations are exposed in surface sediments.

Analysis of the $^{137}Cs/^{241}Am$ activity ratios at Caerlaverock (both sites) indicates that the sediment currently accreting at this site has come from the erosion of other marshes. The $^{137}Cs/^{241}Am$ activity ratios in the upper sections of the cores are higher than expected if the sediment accumulating on the marsh surface has been supplied from an offshore Irish Sea source. The activity ratio values are all greater than 1, suggesting that the sediment accumulating on these sites has come from a source of sediment contaminated by Sellafield discharge at a time of higher ratios. This indicates that sediment is being recycled from the erosion of other marshes. There is some concern that if marshes containing high levels of radionuclides do erode, there will be an increase in exposure to livestock and people using the marshes. Transportation of radionuclides however, also involves a dilution of the overall inventories. The inventories at both Caerlaverock sites are very low and are unlikely to pose an increased risk to those using the marshes. Nevertheless, there may be an increase in exposure caused by surface sediments being stripped from the marsh, as is the case at the eroding Caerlaverock site. This action exposes the higher radionuclide activities *in situ.*

This section indicates that in order to gain a true reflection of the distribution of radionuclides within a saltmarsh system (and therefore develop an effective form of monitoring that distribution), the physical processes operating on the marsh must be understood, not simply in terms of sedimentation rates, but the mechanisms of sedimentation, the size of sediment and the source of sediment.

The chapter as a whole suggests that, although there are internal differences in the development of the individual Solway Firth saltmarshes that result from physiographic location and vegetation, there are also many similarities in the processes operating. This chapter illustrates that the marshes will all respond to estuary wide events, although the form of that response will differ. Integrating the use of geomorphological techniques and radionuclide data has demonstrated that there is a close relationship between saltmarsh sedimentation rates and patterns and the distribution of radionuclides. In addition, the $^{137}Cs/^{241}Am$ activity ratios are able to fingerprint sediments which have been eroded from one marsh, transported and re-deposited on to another marsh.

7.5 Recommendations for future research

This work has raised a number of issues which can only be resolved through further study.

This research has suggested that different modes of sediment deposition operate on Southwick and Caerlaverock compared to Orchardton. At the former two sites, sediment is deposited in pulses which flattens vegetation, thereby producing an alternating sequence of organic-rich and organic-poor strata within the sediment profile. Further investigation is required to determine the physical conditions required to produce these sediment pulses and the frequency with which they occur. For example, are the pulses associated with spring/neap tidal cycles or are they associated with storm activity?

Concomitant with this pattern of sediment deposition is the coincident deposition of radionuclides: high organic layers are associated with higher radionuclide activities. It is suggested in this work, that the parallel pattern of high organic content with high radionuclide inventories results from fine sediment being trapped along with the vegetation as it is flattened by the sediment pulse. This suggestion requires further analysis to answer questions such as: is the relationship between the organic content and radionuclides controlled only by physical processes, such as sediment size, or are also there chemical influences.

That this form of sediment deposition does not occur on Orchardton also requires further investigation. It is suggested in this work (and Bieniowski, 1999 and Stewart, 1999) that sedimentation occurs as sediment is washed from the leaves of *Spartina* in a more gradual process of deposition. However, is this the only form of sedimentation in operation at Orchardton? Enhanced sedimentation appears to occur when *Spartina* occurs beside other pioneer species such as *Puccinellia* and *Salicornia,* but the reasons for this are unclear at present. Does this form of sedimentation occur because of the absence of sediment pulses reaching the head of Orchardton bay?

Indeed the question of the status of Orchardton requires clarification. It seems clear that Orchardton is degrading and that the *Spartina* is experiencing die-back. Further elucidation is required as to the reasons for this. Is there a reduction in the sediment supply because of a lack of erosion of other saltmarsh areas? Is the marsh undergoing shallow subsidence from which current sedimentation rates are unable to compensate. Is the *Spartina* itself creating conditions resulting in its own destruction?

The apparent degradation of Orchardton leads to another issue which requires further study and that is the issue of radionuclide redistribution. This study has cited two forms of radionuclide redistribution: physical redistribution of ^{137}Cs and ^{241}Am resulting from the erosion of saltmarshes and the chemical redissolution of ^{137}Cs. The extent and timescale over which these processes operate needs to be determined. In particular, what factors are important in determining the extent of 137Cs redissolution?

This study has successfully used ^{137}Cs and ^{241}Am radionuclide activities and $^{137}Cs/^{241}Am$ activity ratios as tools to investigate saltmarsh processes. The use of these requires further application.

This study has shown that there is a link between the erosion of some saltmarshes and the accretion of others. Further work is required to determine a sediment budget for the Solway. How much of the material being accreted at the present time is coming from the erosion of other saltmarshes and how much is being supplied from an offshore Irish Sea source? The determination of this budget is important for the future monitoring of radionuclides within the Solway Firth.

This study has suggested that some of the sedimentation patterns (an by association the radionuclide patterns) have resulted due to processes operating on an estuary wide scale. Further investigation is required to determine the extent of estuary wide controls and to assess whether the processes operating within the Solway are also operating at an Irish Sea scale. For example, can the erosional events identified at Southwick and Caerlaverock be identified elsewhere in the Irish Sea?

Although this work has contributed to knowledge of saltmarsh development, the physical and chemical behaviour of certain radionuclides, the relationship between saltmarshes and radionuclides and increased awareness of processes operating in the Solway Firth, this section indicates that there remains questions to be answered.

8 CONCLUSIONS

The following conclusions can be made reflecting the original aims of the work.

The saltmarshes of the Solway Firth are generally reported in the literature as a single entity because they are located within a discrete estuarine unit. In Chapter 3 it was established that there exists a great deal of variability between the different marshes, resulting largely from their physiographic location, vegetation and land use. Few studies have investigated the influence of physiographic location on saltmarsh development, therefore this was viewed as a primary aim.

This study has revealed that there is indeed extensive variability in the Solway Firth saltmarshes in terms of their sedimentation patterns and rates and this is partly a consequence of physiographic location. Orchardton marsh is currently undergoing degradation resulting from a shortage of sediment reaching the head of the deeply incised bay within which it is located. The variations however, cannot simply be attributed to location, factors such as vegetation and wave/tidal energy also play a part in determining how a saltmarsh will develop. The study has also shown that there are similarities in the manner in which the saltmarshes respond to events that originate in the estuary.

The above conclusions were made possible by being able to compare the development histories of the Solway saltmarshes. The sedimentation patterns were investigated by successfully integrating techniques measuring contemporary rates and those measuring more historical rates. The use of contaminant radionuclides from Sellafield to determine both sedimentation rates and sedimentation patterns has been particularly successful.

From establishing these histories it has been shown that a significant difference between the saltmarshes is the type of pioneer vegetation present on the saltmarsh: on Southwick and Caerlaverock it is *Puccinellia,* whilst on Orchardton it is *Spartina.* The vegetation has resulted in differences being experienced in terms of both the extent and method of sedimentation.

Overall sedimentation on Southwick and Caerlaverock is high, especially on those parts of the marsh which are inundated frequently, as would be expected. The sedimentation rates on Orchardton are much lower, indeed so low that it is concluded that the marsh is degrading. It is concluded that the existence of *Spartina* on the marsh is contributing to this degraded state. The *Spartina* does not provide the marsh with a complete vegetation cover, leaving the sediment vulnerable to re-entrainment by successive tides.

The different forms of pioneer vegetation has also resulted in different methods of sediment deposition. It is concluded that on marshes colonised by *Puccinellia,* sediment is deposited on the marsh in pulses, which flattens the vegetation, leading to a sediment profile which alternates high and low organic layers. This profile is not evident at Orchardton indicating a more gradual form of sedimentation.

A large proportion of the study has involved using the pattern of Sellafield contaminants as a tool to investigate saltmarsh development processes. The use of ^{137}Cs and ^{241}Am activity profiles and the profiles of $^{137}Cs/^{241}Am$ activity ratios revealed a number of sedimentation patterns which could have been established otherwise. Of particular interest was the indication of two erosional phases in 1981 and 1986 on Southwick Merse and that sediment is being recycled from marsh to marsh.

In addition to this, the pattern of radionuclides has also been elucidated because of an increased understanding of saltmarsh processes. It has been shown that in dynamic parts of the saltmarsh system, such as areas of mudflat or rapidly accreting areas, there is a general increase in radionuclide activities with depth, but there are no sub-surface maxima. The $^{137}Cs/^{241}Am$ activity ratio profiles reveal a homogenous pattern due to intense mixing of the sediment. In more stable parts of the marsh with lower sedimentation rates, sub-surface maxima qualitatively equating to high discharges from Sellafield in the 1970s are evident. The depth at which these maxima are found relates directly to the sedimentation rate on that part of the marsh. The maxima are found a lower depths in areas which are subject to more frequent tidal inundation, i.e. at the seaward edges of the marsh and adjacent to tidal creeks.

The pattern of radionuclide distribution is also shaped by the mechanism of sediment deposition outlined above. There is parity between the profiles of organic content and radionuclide activity: peaks and toughs in the organic content of the sediment are coincident with peaks and troughs in radionuclide activity. Therefore it can be concluded that as vegetation is trapped under an influx of sediment, radionuclides are also trapped. The explanation offered for this is that very fine sediment, to which radionuclide preferentially sorbed, is trapped in the vegetation as it is flattened.

There are indications that sediment size also has a role to play in the distribution of radionuclides in the Solway Firth. The highest activities of ^{137}Cs and ^{241}Am are located in Orchardton, which appears to have finer sediment characteristics. However, this is not the whole story because although Orchardton has the highest activities it does not have the highest inventories. The conclusion is that the Orchardton sediment supply is coming from a mixed source: from previously eroded saltmarshes and from sediment from the Solway Firth seabed. Results from Caerlaverock also indicate that saltmarshes which are supplied with sediment recycled from other saltmarshes are mixed to such an extent that the radionuclide inventory is very low. That the material is recycled is determined from examining the $^{137}Cs/^{241}Am$ ratio: a higher ration suggests older, recycled material.

The final aim of this project was to explore the extent to which post depositional processes affects the distribution and concentration of ^{137}Cs and ^{241}Am. This has been partly addressed in the above paragraph. The physical redistribution of sediment within the Solway Firth also results in a physical redistribution of radionuclides. The result of this is that overall activities are diluted. In addition to physical dispersion, there is chemical redissolution of ^{137}Cs within the saltmarsh sediments which results in migration and re-deposition of the radionuclide deeper in the sediment profile.

In summary, this study has successfully integrated the use of geomorphological methodologies with radionuclide analysis to investigate saltmarsh processes in the Solway Firth.

GEOMORPHOLOGICAL CONTROLS ON THE SEDIMENTATION PATTERNS OF, AND DISTRIBUTION OF ANTHROPOGENIC RADIONUCLIDES IN, COASTAL SALTMARSHES, SOUTH-WEST SCOTLAND

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DECLARATION

Except where specific reference is made to other sources, the work presented in this thesis is the original work of the author. It has not been submitted, in part or in whole, for any other degree.

Mhairi Harvey.

Mhairi M Harvey

ABSTRACT

The saltmarshes within the Solway Firth are often regarded as a single unit, all experiencing similar physical conditions. This work demonstrates that they are different, each with a unique characteristic and quality. These qualities are identified and a new classification system for the Solway saltmarshes is proposed.

With reference to these differences, the study investigates variations evident in sedimentation patterns utilising a number of methods which operate over different timescales. These methods are successfully integrated to provide a historical analysis of the dynamic nature of the Solway saltmarshes. The results indicate that the Solway marshes undergo rapid change and that this change is related largely to hydroperiod and vegetational influences.

An integral part of this work is the utilisation of Sellafield derived contaminants as a tool to investigate sedimentation patterns. In addition to this, the distributions of the radionuclides are examined and interpreted with reference to the sedimentary status of the marshes under investigation.

Many authors consider accreting saltmarshes to be long term stores for radioactive contaminants but this study demonstrates that physical and chemical dispersion of some radionuclide species indicates that the saltmarsh store is ephemeral.

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APPENDIX 1

SOUTHWICK RESULTS

Plate	Position on Marsh	October '95	June '96	August '97	Net accretion/erosion		**Accretion rate**
		Average depth (mm)	Average depth (mm)	Average depth (mm)	8 months (mm)	22 months (mm)	**(cm y^{-1})**
1	High marsh	98	110	138	12	40	**2.2**
2	High marsh	95	104	118	9	23	**1.3**
3	High marsh	97	112	150	15	53	**2.9**
4	Middle marsh - nr. creek	91	105	126	14	35	**1.9**
5a	Middle marsh - nr. creek	82	96	n/f	14	*	**2.1**
5b	Middle marsh	80	92	117	12	37	**2.0**
6	Middle marsh	138	150	168	12	30	**1.6**
7	Middle marsh	81	102	143	21	62	**3.4**
8	Middle marsh - nr. creek	84	110	133	26	49	**2.7**
9	Middle marsh - nr. creek	87	115	134	28	47	**2.6**
10	Middle marsh - nr. creek	96	122	128	26	32	**1.7**
11	Middle marsh - nr. creek	108	118	155	10	47	**2.6**
12	Slumped creek bank	103	160	n/f	57	*	**8.6**
13	Slumped creek bank	107	165	156	58	49	**2.7**
14	Middle marsh	108	132	192	24	84	**4.6**
15	Middle marsh - nr. creek	62	104	n/f	42	*	**6.3**
16	Middle marsh - nr. creek	86	100	127	14	41	**2.2**
17	Middle marsh	102	122	154	20	52	**2.8**
18	Inner bend of creek meander	104	n/f	n/f	*	*	*
19	Inner bend of creek meander	99	n/f	n/f	*	*	*
20	Middle marsh - nr. creek	78	140	n/f	62	*	**9.3**
21	Middle marsh	107	138	200	31	93	**5.1**
22	Pioneer marsh - *Puccinellia*	118	n/f	n/f	*	*	*
23	Mudflat	105	200	144	95	39	**2.1**
24	Mudflat - nr. channel	104	69	n/f	-35	*	**-5.3**
25	Mudflat - nr. channel	85	100	n/f	15	*	**2.3**
26	Mudflat	115	n/f	n/f	*	*	*

n/f = not found
* = unable to calculate

Table (i) Southwick sedimentation plate results

Loss on Ignition Southwick					
SWA		SWB		SWC	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	2.66	0.01	2.77	0.01	4.33
0.04	2.32	0.04	3.17	0.03	4.18
0.06	2.30	0.06	3.52	0.06	2.77
0.09	3.05	0.08	3.38	0.08	3.98
0.12	2.12	0.11	4.53	0.10	4.18
0.14	1.71	0.13	3.16	0.13	4.70
0.17	2.73	0.15	3.21	0.15	2.53
0.19	2.51	0.18	3.58	0.17	3.15
0.22	2.49	0.20	2.97	0.19	4.18
0.25	2.98	0.23	3.70	0.22	4.40
0.27	2.53	0.25	4.57	0.24	2.56
0.30	2.39	0.27	1.98	0.26	4.36
0.32	2.69	0.30	2.29	0.28	3.17
0.35	2.50	0.32	4.14	0.31	3.35
0.37	2.50	0.35	2.33	0.33	3.01
0.40	2.55	0.37	2.19	0.35	2.35
0.43	2.31	0.39	2.33	0.38	1.95
0.45	2.88	0.42	2.18	0.40	3.37
0.48	2.60	0.44	2.55	0.42	3.57
0.50	3.91	0.46	2.96	0.44	4.17
0.53	3.07	0.49	3.31	0.47	2.77
0.55	3.13	0.51	3.34	0.49	2.99
0.58	3.09	0.54	3.37	0.51	3.42
0.61	2.51	0.56	4.36	0.53	5.02
0.63	1.75	0.58	2.37	0.56	3.99
0.66	0.99	0.61	2.99	0.58	4.00
0.68	3.39	0.63	2.56	0.60	2.59
0.71	3.74	0.65	2.40	0.63	2.57
0.74	3.24	0.68	2.77	0.65	4.00
0.76	2.69	0.70	2.37	0.67	3.35
0.79	2.99	0.73	2.57	0.69	2.78
0.81	3.07	0.75	2.38	0.72	2.98
0.84	3.98	0.77	2.36	0.74	2.75
0.86	3.74	0.80	2.17	0.76	2.92
0.89	4.26	0.82	2.92	0.78	3.16
0.92	4.16	0.85	3.33	0.81	2.61
0.94	3.35	0.87	3.37	0.83	3.55
0.97	5.56	0.89	2.87	0.85	3.82
		0.92	2.79	0.88	3.76
		0.94	2.35	0.90	3.79
		0.96	2.95	0.92	2.76
		0.99	3.91	0.94	2.56
				0.97	2.77
				0.99	3.59

Table (ii) Loss on ignition results - Cores SWA, SWB, SWC

Loss on Ignition Southwick					
SWD		SWE		SWF	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	2.38	0.01	2.14	0.01	3.70
0.03	2.34	0.04	2.12	0.04	3.31
0.06	2.56	0.06	1.75	0.06	3.82
0.08	2.96	0.08	2.36	0.08	4.11
0.10	2.53	0.11	2.71	0.11	2.16
0.13	0.99	0.13	2.97	0.13	4.40
0.15	3.94	0.15	2.66	0.15	3.81
0.17	3.60	0.18	2.37	0.18	2.73
0.20	2.37	0.20	2.76	0.20	2.20
0.22	3.37	0.23	2.30	0.22	2.36
0.24	1.58	0.25	2.94	0.25	2.94
0.27	2.77	0.27	3.35	0.27	4.42
0.29	3.35	0.30	2.93	0.29	3.93
0.31	2.57	0.32	3.94	0.32	4.79
0.34	3.76	0.35	3.55	0.34	2.85
0.36	4.19	0.37	2.51	0.36	3.31
0.38	3.33	0.39	2.71	0.39	2.67
0.41	4.17	0.42	2.94	0.41	3.02
0.43	3.39	0.44	3.74	0.44	3.56
0.45	3.34	0.46	4.25	0.46	2.15
0.48	2.75	0.49	4.35	0.48	2.68
0.50	3.57	0.51	3.34	0.51	2.00
0.52	2.38	0.54	3.50	0.53	2.12
0.55	2.20	0.56	3.16	0.55	2.93
0.57	2.38	0.58	3.72	0.58	3.86
0.59	2.93	0.61	3.98	0.60	2.61
0.62	2.58	0.63	3.59	0.62	2.69
0.64	1.60	0.65	3.94	0.65	3.63
0.66	1.98	0.68	3.17	0.67	4.14
0.69	3.61	0.70	2.96	0.69	3.92
0.71	3.79	0.73	2.75	0.72	4.58
0.73	2.77	0.75	2.95	0.74	4.73
0.76	1.57	0.77	4.37	0.76	3.91
0.78	2.55	0.80	4.14	0.79	3.51
0.80	2.97	0.82	3.75	0.81	3.33
0.83	3.59	0.85	3.37	0.84	4.19
0.85	3.36	0.87	3.93	0.86	3.75
0.87	2.99	0.89	3.37	0.88	3.75
0.90	3.61	0.92	3.19	0.91	2.71
0.92	3.63	0.94	3.33	0.93	3.36
0.94	3.35	0.96	2.34	0.95	3.96
0.97	3.54	0.99	2.95	0.98	3.90
0.99	3.21			1.00	3.68

Table (ii, cont.) Loss on ignition results - Cores SWD, SWE, SWF

Loss on Ignition Southwick					
SWG		SWH		SWJ	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	4.36	0.01	3.56	0.01	5.77
0.03	3.45	0.03	2.64	0.03	5.08
0.06	3.45	0.06	3.17	0.06	5.48
0.08	3.35	0.08	2.73	0.08	3.58
0.10	3.13	0.10	3.09	0.10	4.39
0.12	3.50	0.13	2.48	0.13	2.82
0.14	2.74	0.15	3.32	0.15	4.53
0.17	3.14	0.17	2.45	0.17	5.13
0.19	2.95	0.20	3.27	0.19	5.81
0.21	4.37	0.22	2.33	0.22	8.30
0.23	4.14	0.24	3.74	0.24	4.69
0.26	4.29	0.27	3.61	0.26	3.94
0.28	3.16	0.29	3.42	0.28	4.52
0.30	2.98	0.31	3.19	0.31	5.26
0.32	2.77	0.34	5.42	0.33	5.12
0.34	3.13	0.36	2.75	0.35	6.43
0.37	2.70	0.38	3.33	0.38	5.72
0.39	3.32	0.41	2.94	0.40	4.68
0.41	3.59	0.43	3.11	0.42	5.63
0.43	3.89	0.45	1.93	0.44	5.33
0.46	4.53	0.48	4.04	0.47	4.28
0.48	3.59	0.50	3.32	0.49	4.39
0.50	3.17	0.52	4.19	0.51	3.44
0.52	3.71	0.55	4.53	0.53	3.96
0.54	2.18	0.57	3.49	0.56	4.10
0.57	3.76	0.59	3.50	0.58	3.90
0.59	4.10	0.62	3.43	0.60	3.82
0.61	3.29	0.64	4.32	0.63	3.76
0.63	2.53	0.66	3.81	0.65	3.85
0.66	2.75	0.69	3.49	0.67	2.79
0.68	2.17	0.71	1.96	0.69	4.05
0.70	3.79	0.73	2.77	0.72	4.87
0.72	3.16	0.76	3.50	0.74	4.29
0.74	2.56	0.78	2.94	0.76	4.41
0.77	3.39	0.80	2.56	0.78	4.21
0.79	4.34	0.83	2.87	0.81	3.33
0.81	4.95	0.85	2.38	0.83	2.70
0.83	4.17	0.87	1.98	0.85	2.30
0.86	4.02	0.90	2.19	0.88	2.23
0.88	3.52	0.92	2.74	0.90	2.49
0.90	3.24	0.94	2.94	0.92	1.49
0.92	3.01	0.97	2.55	0.94	1.51
0.94	2.91	0.99	2.97	0.97	1.87
0.97	2.58			0.99	1.89
0.99	2.55				

Table (ii, cont.) Loss on ignition results - Cores SWG, SWH, SWJ

Loss on Ignition Southwick	
SWK	
Sample (m)	Loss on ignition (%)
0.01	4.99
0.03	3.86
0.05	3.50
0.08	2.51
0.10	3.02
0.12	4.03
0.14	3.88
0.16	3.48
0.18	4.07
0.21	4.40
0.23	4.71
0.25	3.30
0.27	3.11
0.29	4.00
0.32	3.17
0.34	3.29
0.36	3.53
0.38	3.77
0.40	4.28
0.42	3.38
0.45	2.84
0.47	2.57
0.49	1.96
0.51	1.37
0.53	1.96
0.55	2.20
0.58	2.53
0.60	2.40
0.62	2.38
0.64	3.40
0.66	2.66
0.68	2.91
0.71	2.11
0.73	2.30
0.75	2.14
0.77	1.55
0.79	1.79
0.82	2.10
0.84	1.98
0.86	2.17
0.88	1.72
0.90	1.15
0.92	1.55
0.95	1.80
0.97	1.57
0.99	1.29

Table (ii, cont.) Loss on ignition results - Core SWK

Radionuclide Specific Activities and Activity Ratios Core SWA						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	144	6	144	6	1.0
0.03	0.04	121	5	86	5	1.4
0.05	0.06	104	3	80	2	1.3
0.07	0.09	132	5	94	4	1.4
0.09	0.12	110	3	40	1	2.8
0.11	0.14	100	5	91	4	1.1
0.13	0.17	127	3	117	3	1.1
0.15	0.19	132	5	116	4	1.1
0.17	0.22	107	2	97	2	1.1
0.19	0.25	145	6	133	5	1.1
0.21	0.27	222	4	151	3	1.5
0.23	0.30	163	7	136	6	1.2
0.25	0.32	158	7	143	6	1.1
0.27	0.35	143	3	119	3	1.2
0.29	0.37	164	3	137	3	1.2
0.31	0.40	167	3	168	3	1.0
0.33	0.43	142	6	116	5	1.2
0.35	0.45	215	7	194	5	1.1
0.37	0.48	167	6	117	4	1.4
0.39	0.50	215	4	181	3	1.2
0.41	0.53	143	8	117	6	1.2
0.43	0.55	167	6	142	4	1.2
0.45	0.58	167	3	143	3	1.2
0.47	0.61	167	5	142	4	1.2
0.49	0.63	119	3	104	2	1.1
0.51	0.66	46	4	39	2	1.2
0.53	0.68	143	3	117	2	1.2
0.55	0.71	215	3	181	2	1.2
0.57	0.74	215	7	142	4	1.5
0.59	0.76	191	9	156	6	1.2
0.61	0.79	239	8	181	6	1.3
0.63	0.81	191	4	116	2	1.6
0.65	0.84	215	7	155	5	1.4
0.67	0.86	191	7	116	5	1.6
0.69	0.89	288	5	181	3	1.6
0.71	0.92	288	8	194	5	1.5
0.73	0.94	264	9	168	6	1.6
0.76	0.98	264	5	207	3	1.3

Table (iii) Radionuclide Specific Activities and Activity Ratios - Core SWA

Radionuclide Specific Activities and Activity Ratios Core SWB						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	191	8	182	8	1.1
0.03	0.04	264	4	207	3	1.3
0.05	0.06	239	6	207	5	1.2
0.07	0.08	240	4	233	4	1.0
0.09	0.11	361	4	324	4	1.1
0.11	0.13	288	8	259	7	1.1
0.13	0.15	288	5	285	5	1.0
0.15	0.18	288	5	272	4	1.1
0.17	0.20	191	7	181	6	1.1
0.19	0.23	240	8	220	7	1.1
0.21	0.25	336	6	298	5	1.1
0.23	0.27	143	5	117	4	1.2
0.25	0.30	191	3	155	3	1.2
0.27	0.32	456	12	440	12	1.0
0.29	0.35	264	8	181	6	1.5
0.31	0.37	215	3	130	2	1.7
0.33	0.39	288	10	155	5	1.9
0.35	0.42	481	15	220	7	2.2
0.37	0.44	771	10	324	4	2.4
0.39	0.46	892	25	440	12	2.0
0.41	0.49	1038	26	686	17	1.5
0.43	0.51	965	18	609	11	1.6
0.45	0.54	990	25	583	14	1.7
0.47	0.56	626	9	310	4	2.0
0.49	0.58	700	19	363	10	1.9
0.51	0.61	707	10	388	5	1.8
0.53	0.63	486	14	295	9	1.6
0.55	0.65	443	13	359	10	1.2
0.57	0.68	436	12	487	14	0.9
0.59	0.70	389	6	477	8	0.8
0.61	0.73	332	11	236	8	1.4
0.63	0.75	245	4	157	3	1.6
0.65	0.77	223	9	158	6	1.4
0.67	0.80	174	7	123	5	1.4
0.69	0.82	194	4	189	4	1.0
0.71	0.85	211	12	255	15	0.8
0.73	0.87	196	10	26	1	7.6
0.75	0.89	184	9	268	13	0.7
0.77	0.92	186	8	364	16	0.5
0.79	0.94	182	3	308	5	0.6
0.81	0.96	184	10	310	17	0.6
0.83	0.99					

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWB

Radionuclide Specific Activities and Activity Ratios Core SWC						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	155	6	125	5	1.2
0.03	0.03	203	6	198	6	1.0
0.05	0.06	164	3	161	3	1.0
0.07	0.08	221	8	184	7	1.2
0.09	0.10	207	3	191	3	1.1
0.11	0.13	264	8	263	7	1.0
0.13	0.15	111	4	109	4	1.0
0.15	0.17	180	6	163	5	1.1
0.17	0.19	291	8	281	7	1.0
0.19	0.22	333	9	336	7	1.0
0.21	0.24	139	6	118	5	1.2
0.23	0.26	291	4	290	4	1.0
0.25	0.28	167	4	191	4	0.9
0.27	0.31	222	3	199	3	1.1
0.29	0.33	194	5	163	4	1.2
0.31	0.35	277	4	245	3	1.1
0.33	0.38	180	5	145	4	1.2
0.35	0.40	333	4	282	3	1.2
0.37	0.42	347	7	309	5	1.1
0.39	0.44	416	9	363	7	1.1
0.41	0.47	277	4	245	3	1.1
0.43	0.49	444	10	399	8	1.1
0.45	0.51	471	11	335	8	1.4
0.47	0.53	678	19	525	11	1.3
0.49	0.56	499	15	508	12	1.0
0.51	0.58	583	7	408	5	1.4
0.53	0.60	374	7	209	4	1.8
0.55	0.63	472	11	318	7	1.5
0.57	0.65	679	15	435	10	1.6
0.59	0.67	458	6	299	4	1.5
0.61	0.69	402	10	245	7	1.6
0.63	0.72	402	8	199	4	2.0
0.65	0.74	458	12	227	7	2.0
0.67	0.76	610	8	299	4	2.0
0.69	0.78	514	9	263	5	2.0
0.71	0.81	348	10	226	6	1.5
0.73	0.83	636	7	376	4	1.7
0.75	0.85	675	14	413	9	1.6
0.77	0.88	692	13	253	6	2.7
0.79	0.90	1022	12	481	6	2.1
0.81	0.92	539	13	262	8	2.1
0.83	0.94	554	12	243	7	2.3
0.85	0.97	687	15	320	9	2.1
0.87	0.99	861	10	333	4	2.6

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWC

Radionuclide Specific Activities and Activity Ratios Core SWD						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	143	3	142	2	1.0
0.03	0.03	167	5	169	4	1.0
0.05	0.06	191	4	181	3	1.1
0.07	0.08	191	6	181	4	1.1
0.09	0.10	191	3	194	2	1.0
0.11	0.13	94	4	65	2	1.5
0.13	0.15	239	7	246	6	1.0
0.15	0.17	264	5	246	4	1.1
0.17	0.20	143	5	116	4	1.2
0.19	0.22	240	4	233	3	1.0
0.21	0.24	167	6	129	4	1.3
0.23	0.27	215	4	194	3	1.1
0.25	0.29	264	9	207	6	1.3
0.27	0.31	191	3	155	3	1.2
0.29	0.34	361	12	285	8	1.3
0.31	0.36	385	12	324	9	1.2
0.33	0.38	384	11	298	8	1.3
0.35	0.41	529	8	440	6	1.2
0.37	0.43	385	12	350	9	1.1
0.39	0.45	481	16	272	9	1.8
0.41	0.48	288	10	194	7	1.5
0.43	0.50	481	7	336	5	1.4
0.45	0.52	336	11	194	6	1.7
0.47	0.55	305	10	203	6	1.5
0.49	0.57	360	5	194	3	1.9
0.51	0.59	387	5	289	4	1.3
0.53	0.62	455	10	277	7	1.6
0.55	0.64	286	5	168	3	1.7
0.57	0.66	385	9	255	6	1.5
0.59	0.69	643	20	476	13	1.4
0.61	0.71	387	5	289	4	1.3
0.63	0.73	455	10	277	7	1.6
0.65	0.76	286	5	168	3	1.7
0.67	0.78	385	9	255	6	1.5
0.69	0.80	643	20	476	13	1.4

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWD

Radionuclide Specific Activities and Activity Ratios Core SWE						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	128	3	106	3	1.2
0.03	0.04	166	6	131	4	1.3
0.05	0.06	131	3	116	3	1.1
0.07	0.08	156	4	134	3	1.2
0.09	0.11	139	5	132	4	1.0
0.11	0.13	164	4	164	3	1.0
0.13	0.15	152	5	158	5	1.0
0.15	0.18	150	3	143	3	1.1
0.17	0.20	153	7	142	7	1.1
0.19	0.23	155	7	144	6	1.1
0.21	0.25	188	6	153	6	1.2
0.23	0.27	214	4	187	3	1.1
0.25	0.30	198	7	186	6	1.1
0.27	0.32	237	4	232	4	1.0
0.29	0.35	211	7	202	6	1.0
0.31	0.37	175	8	154	6	1.1
0.33	0.39	195	4	190	3	1.0
0.35	0.42	218	7	218	6	1.0
0.37	0.44	243	4	224	3	1.1
0.39	0.46	266	8	218	6	1.2
0.41	0.49	267	5	241	4	1.1
0.43	0.51	180	6	167	5	1.1
0.45	0.54	224	4	189	3	1.2
0.47	0.56	224	7	174	6	1.3
0.49	0.58	246	9	216	7	1.1
0.51	0.61	257	5	251	4	1.0
0.53	0.63	262	8	251	7	1.0
0.55	0.65	286	10	242	7	1.2
0.57	0.68	271	5	227	4	1.2
0.59	0.70	240	7	245	6	1.0
0.61	0.73	211	4	187	3	1.1
0.63	0.75	252	9	212	8	1.2
0.65	0.77	510	15	387	11	1.3
0.67	0.80	424	13	377	11	1.1
0.69	0.82	368	13	274	9	1.3
0.71	0.85	283	8	245	6	1.2
0.73	0.87	485	7	351	5	1.4
0.75	0.89	334	11	244	8	1.4
0.77	0.92	292	8	216	7	1.3
0.79	0.94	341	6	247	4	1.4
0.81	0.96	285	10	160	7	1.8
0.83	0.99	292	9	198	6	1.5

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWE

Radionuclide Specific Activities and Activity Ratios Core SWF						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	176	5	153	4	1.1
0.03	0.04	201	7	208	7	1.0
0.05	0.06	234	4	216	3	1.1
0.07	0.08	258	9	261	8	1.0
0.09	0.11	118	4	97	3	1.2
0.11	0.13	302	10	286	9	1.1
0.13	0.15	301	12	278	10	1.1
0.15	0.18	209	7	191	6	1.1
0.17	0.20	191	7	202	6	0.9
0.19	0.22	240	8	211	7	1.1
0.21	0.25	262	9	225	8	1.2
0.23	0.27	481	10	405	8	1.2
0.25	0.29	453	12	390	10	1.2
0.27	0.32	667	8	541	6	1.2
0.29	0.34	462	12	260	9	1.8
0.31	0.36	529	17	381	13	1.4
0.33	0.39	441	12	258	8	1.7
0.35	0.41	396	9	235	7	1.7
0.37	0.44	581	7	259	4	2.2
0.39	0.46	388	9	166	6	2.3
0.41	0.48	722	14	345	8	2.1
0.43	0.51	702	15	317	9	2.2
0.45	0.53	493	6	188	2	2.6
0.47	0.55	838	15	352	8	2.4
0.49	0.58	1188	20	429	10	2.8
0.51	0.60	937	11	316	4	3.0
0.53	0.62	940	18	343	9	2.7
0.55	0.65	963	14	325	6	3.0
0.57	0.67	909	11	280	4	3.3
0.59	0.69	941	16	339	8	2.8
0.61	0.72	1093	17	394	8	2.8
0.63	0.74	1287	22	526	12	2.4
0.65	0.76	1049	20	426	11	2.5
0.67	0.79	1100	23	501	14	2.2
0.69	0.81	900	18	369	10	2.4
0.71	0.84	1063	24	439	14	2.4
0.73	0.86	1298	27	519	14	2.5
0.75	0.88	1196	14	412	5	2.9
0.77	0.91	897	16	253	8	3.5
0.79	0.93	1084	15	364	7	3.0
0.81	0.95	345	9	209	4	1.7
0.83	0.98	955	23	394	13	2.4

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWF

Radionuclide Specific Activities and Activity Ratios Core SWG						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity (Bq kg^{-1})	^{137}Cs Error (Bq kg^{-1})	^{241}Am Specific Activity (Bq kg^{-1})	^{241}Am Error (Bq kg^{-1})	$^{137}Cs/^{241}Am$ Activity Ratio
0.01	0.01	229	5	217	4	1.1
0.03	0.03	247	4	234	4	1.1
0.05	0.06	234	3	8	1	28.8
0.07	0.08	277	6	210	5	1.3
0.09	0.10	242	8	223	7	1.1
0.11	0.12	397	6	328	5	1.2
0.13	0.14	332	10	272	11	1.2
0.15	0.17	247	7	239	6	1.0
0.17	0.19	302	5	252	4	1.2
0.19	0.21	524	10	492	8	1.1
0.21	0.23	519	15	468	12	1.1
0.23	0.26	764	10	738	9	1.0
0.25	0.28	719	16	385	10	1.9
0.27	0.30	417	11	234	8	1.8
0.29	0.32	549	6	261	3	2.1
0.31	0.34	825	20	405	12	2.0
0.33	0.37	660	12	347	8	1.9
0.35	0.39	1206	23	509	12	2.4
0.37	0.41	1160	14	463	6	2.5
0.39	0.43	1254	25	505	14	2.5
0.41	0.46	1510	30	648	17	2.3
0.43	0.48	1447	24	604	12	2.4
0.45	0.50	1205	24	489	13	2.5
0.47	0.52	933	21	611	19	1.5
0.49	0.54	836	10	342	5	2.4
0.51	0.57	1607	28	808	17	2.0
0.53	0.59	1655	25	724	13	2.3
0.55	0.61	1557	33	521	16	3.0
0.57	0.63	1040	23	436	13	2.4
0.59	0.66	1498	34	817	22	1.8
0.61	0.68	1002	12	648	7	1.5
0.63	0.70	1316	26	807	17	1.6
0.65	0.72	1218	27	997	22	1.2
0.67	0.74	815	16	382	9	2.1
0.69	0.77	1041	28	875	22	1.2
0.71	0.79	1272	30	705	19	1.8
0.73	0.81	1080	25	630	17	1.7
0.75	0.83	805	9	533	6	1.5
0.77	0.86	646	17	370	11	1.7
0.79	0.88	461	14	250	10	1.8
0.81	0.90	337	11	272	8	1.2
0.83	0.92	257	9	217	8	1.2
0.85	0.94	207	3	105	2	2.0
0.87	0.97	151	4	4	0.2	35.8
0.89	0.99	143	3	5	0.1	26.5

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWG

Radionuclide Specific Activities and Activity Ratios Core SWH						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.01	0.01	225	8	183	6	1.2
0.03	0.03	228	4	209	4	1.1
0.05	0.06	221	7	185	6	1.2
0.07	0.08	216	9	197	7	1.1
0.09	0.10	197	10	177	8	1.1
0.11	0.13	187	4	158	4	1.2
0.13	0.15	269	5	272	4	1.0
0.15	0.17	301	11	271	9	1.1
0.17	0.20	246	7	231	5	1.1
0.19	0.22	191	6	181	5	1.1
0.21	0.24	287	5	229	4	1.3
0.23	0.27	250	5	207	4	1.2
0.25	0.29	424	5	65	2	6.6
0.27	0.31	483	11	359	8	1.3
0.29	0.34	652	18	522	14	1.2
0.31	0.36	448	7	223	4	2.0
0.33	0.38	467	15	297	10	1.6
0.35	0.41	377	11	237	7	1.6
0.37	0.43	543	8	276	5	2.0
0.39	0.45	445	11	203	6	2.2
0.41	0.48	784	23	394	13	2.0
0.43	0.50	637	9	296	5	2.2
0.45	0.52	1037	24	493	14	2.1
0.47	0.55	1213	25	507	13	2.4
0.49	0.57	1080	13	441	5	2.5
0.51	0.59	1061	12	350	4	3.0
0.53	0.62	1307	33	489	16	2.7
0.55	0.64	1621	45	645	23	2.5
0.57	0.66	1254	31	546	17	2.3
0.59	0.69	1484	37	590	20	2.5
0.61	0.71	996	26	364	13	2.7
0.63	0.73	1387	34	525	18	2.6
0.65	0.76	1369	17	468	7	2.9
0.67	0.78	1222	27	427	13	2.9
0.69	0.80	964	19	355	10	2.7
0.71	0.83	1073	12	415	5	2.6
0.73	0.85	1289	24	642	14	2.0
0.75	0.87	1312	26	479	13	2.7
0.77	0.90	1349	17	419	6	3.2
0.79	0.92	1204	22	469	11	2.6
0.81	0.94	1240	21	537	11	2.3
0.83	0.97	1280	27	762	18	1.7
0.85	0.99	1148	19	647	12	1.8

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWH

Radionuclide Specific Activities and Activity Ratios Core SWJ						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	248	4	270	4	0.9
0.03	0.03	210	6	220	6	1.0
0.05	0.06	258	7	265	7	1.0
0.07	0.08	198	3	181	3	1.1
0.09	0.10	298	8	298	8	1.0
0.11	0.13	243	7	236	7	1.0
0.13	0.15	284	4	285	4	1.0
0.15	0.17	323	5	276	4	1.2
0.17	0.19	517	13	455	11	1.1
0.19	0.22	822	17	659	14	1.2
0.21	0.24	699	15	469	12	1.5
0.23	0.26	644	17	411	13	1.6
0.25	0.28	494	6	140	3	3.5
0.27	0.31	687	16	371	11	1.9
0.29	0.33	714	13	374	9	1.9
0.31	0.35	1521	25	653	14	2.3
0.33	0.38	1467	30	603	17	2.4
0.35	0.40	1422	16	562	6	2.5
0.37	0.42	1553	28	710	17	2.2
0.39	0.44	1559	21	645	10	2.4
0.41	0.47	1220	24	535	14	2.3
0.43	0.49	1377	23	592	13	2.3
0.45	0.51	1248	15	587	7	2.1
0.47	0.53	1870	30	110	2	17.0
0.49	0.56	1584	29	629	16	2.5
0.51	0.58	1132	16	521	9	2.2
0.53	0.60	1305	15	748	9	1.7
0.55	0.63	1138	14	687	8	1.7
0.57	0.65	1097	17	1154	17	1.0
0.59	0.67	472	6	402	5	1.2
0.61	0.69	1044	12	700	8	1.5
0.63	0.72	993	18	531	12	1.9
0.65	0.74	462	19	426	14	1.1
0.67	0.76	534	12	309	8	1.7
0.69	0.78	414	12	262	9	1.6
0.71	0.81	297	4	15	2.2	20.3
0.73	0.83	254	7	189	6	1.3
0.75	0.85	217	6	71	6.4	3.0
0.77	0.88	114	2	60	1.7	1.9
0.79	0.90	83	4	114	4.5	0.7
0.81	0.92					
0.83	0.94					

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWJ

Radionuclide Specific Activities and Activity Ratios
Core SWK

Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity ($Bq\ kg^{-1}$)	^{137}Cs Error ($Bq\ kg^{-1}$)	^{241}Am Specific Activity ($Bq\ kg^{-1}$)	^{241}Am Error ($Bq\ kg^{-1}$)	$^{137}Cs/^{241}Am$ Activity Ratio
0.01	0.01	257	7	245	7	1.0
0.03	0.03	266	8	272	8	1.0
0.05	0.05	303	4	233	4	1.3
0.07	0.08	256	8	263	8	1.0
0.09	0.10	319	8	316	8	1.0
0.11	0.12	666	19	591	16	1.1
0.13	0.14	673	15	437	11	1.5
0.15	0.16	594	7	297	4	2.0
0.17	0.18	1135	23	580	15	2.0
0.19	0.21	1348	26	574	15	2.3
0.21	0.23	1573	17	633	7	2.5
0.23	0.25	1375	25	617	15	2.2
0.25	0.27	1306	19	527	10	2.5
0.27	0.29	1636	33	927	22	1.8
0.29	0.32	1254	25	588	15	2.1
0.31	0.34	1240	14	739	9	1.7
0.33	0.36	1000	23	839	19	1.2
0.35	0.38	1068	19	679	14	1.6
0.37	0.40	751	15	341	9	2.2
0.39	0.42	492	11	220	7	2.2
0.41	0.45	293	4	88	1.9	3.3
0.43	0.47	226	8	24	4.0	9.4
0.45	0.49	174	3	13	1.1	13.5
0.47	0.51	141	5	14	2.7	9.9
0.49	0.53	101	3	6	1.6	16.8

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core SWK

Sediment Size Analysis (Sieving) Southwick						
		Differential % coarser than seive size				
Depth (m)	Sample weight (g)	500μm	250μm	125μm	63μm	pan
CORE SWA						
0.01	33.67	1.2	2.3	2.2	38.6	55.3
0.27	32.79	0.4	1.7	3.1	44.4	50.0
0.53	25.53	1.0	2.0	26.9	34.0	35.3
0.79	31.02	0.6	1.6	7.8	41.9	47.8
CORE SWB						
0.01	33.75	1.8	3.7	3.7	37.3	53.1
0.25	28.36	1.5	3.3	5.0	35.3	54.6
0.37	31.56	0.4	0.8	2.5	31.3	66.3
0.49	35.79	0.8	2.5	4.6	47.9	43.7
0.54	32.78	0.6	2.1	4.4	27.9	65.5
0.61	29.68	0.2	1.2	3.4	27.7	67.1
0.73	27.89	0.5	1.5	3.0	45.2	49.5
0.96	28.12	0.2	0.9	3.4	46.6	48.5
CORE SWC						
0.01	35.9	1.0	2.5	3.1	40.5	52.5
0.03	31.63	0.9	3.0	4.3	48.9	42.5
0.06	30.07	1.3	2.8	3.2	40.8	51.7
0.08	35.5	1.3	3.5	4.8	37.6	52.3
0.1	30.96	1.5	3.4	4.7	42.3	48.0
0.13	28.9	1.6	4.2	5.2	39.7	48.8
0.15	32.16	0.5	1.2	1.7	48.9	47.5
0.17	31.8	0.7	2.0	3.3	42.5	51.0
0.19	29.44	1.1	3.8	4.9	39.7	50.1
0.22	30.48	1.7	4.7	5.7	40.1	47.6
0.24	34.27	0.4	1.1	1.5	47.8	49.0
0.26	32.52	1.2	3.3	4.6	42.4	47.6
0.28	29.92	0.7	1.7	2.1	45.7	49.1
0.31	35.53	0.9	2.3	3.2	44.7	48.6
0.33	27.53	0.6	2.1	2.8	44.1	50.1
0.35	29.74	1.4	2.8	3.7	26.6	65.7
0.47	30.19	1.0	2.5	3.2	42.3	50.8
0.58	29.42	2.0	4.0	5.4	24.1	64.6
0.69	32.61	1.3	2.6	2.7	42.3	50.7
0.81	31.82	0.8	1.4	2.3	20.1	75.5
0.92	31.89	1.0	2.3	2.8	39.4	54.1
CORE SWD						
0.01	26.34	2.0	3.8	3.5	40.9	49.2
0.24	29.71	0.5	1.3	1.7	49.1	47.0
0.48	32.32	1.1	2.5	2.8	45.8	47.5
0.71	25.59	1.0	2.1	3.2	43.8	49.7
0.94	39.34	6.5	6.3	5.2	36.7	44.7

Table (iv) Sediment Size Analysis Sieving Results - Cores SWA, SWB, SWC, SWD

Sediment Size Analysis (Sieving) Southwick						
		Differential % coarser than seive size				
Depth (m)	Sample weight (g)	500μm	250μm	125μm	63μm	pan
CORE SWE						
0.01	27.42	0.5	0.5	2.2	41.0	53.7
0.25	31.42	1.0	2.5	4.4	41.8	50.0
0.49	32.26	0.6	2.3	4.9	47.9	43.9
0.73	28.97	0.8	1.9	2.9	42.7	51.3
0.85	31.41	0.7	1.9	3.1	14.0	80.5
0.96	24.26	0.6	1.6	2.1	39.2	55.9
CORE SWF						
0.01	27.55	2.7	4.2	4.1	32.7	57.1
0.25	32.24	1.2	2.5	3.1	40.4	52.5
0.36	35.91	2.6	4.3	4.7	24.5	63.9
0.48	33.52	2.9	4.3	4.0	39.7	48.7
0.6	37.06	1.5	3.3	4.5	19.8	70.7
0.72	27.81	1.4	2.8	4.2	36.6	54.4
0.84	27.63	1.2	2.9	4.1	21.4	70.0
0.95	25.69	2.3	5.3	5.2	34.4	52.7
CORE SWG						
0.01	21.24	2.7	4.9	4.3	30.8	56.7
0.12	35.5	1.8	6.8	7.5	17.8	66.1
0.23	29.96	2.8	7.2	6.5	35.8	47.3
0.46	29.2	1.8	5.5	6.7	36.6	48.9
0.57	42.11	2.9	4.5	5.7	21.4	65.1
0.68	25.59	1.0	2.1	3.2	43.8	49.7
0.79	25.13	2.3	4.4	6.4	29.8	57.2
0.9	39.34	6.5	6.3	5.2	36.7	44.7
CORE SWH						
0.01	28.31	2.5	4.2	4.2	33.9	54.6
0.13	23.47	1.0	2.3	3.5	21.5	71.5
0.24	37.2	1.6	3.7	3.7	41.6	49.2
0.48	22.42	1.5	4.5	5.7	47.0	62.3
0.59	23.36	1.6	3.7	5.7	21.6	66.8
0.64	28.43	3.5	5.9	7.6	19.5	63.3
0.71	24.61	1.5	3.1	3.7	37.5	53.8
0.83	29.22	1.4	3.3	4.4	25.1	65.2
0.94	28.03	1.5	3.4	3.9	44.1	46.7
CORE SWJ						
0.01	27.69	2.5	4.9	6.0	39.4	46.6
0.13	29.73	0.7	1.4	2.4	14.3	47.5
0.24	27.44	1.4	3.7	5.2	44.8	44.2
0.47	28.78	1.8	3.8	4.4	42.7	46.8
0.58	28.34	0.3	2.3	3.7	21.8	71.9
0.69	28.02	3.6	5.3	6.0	42.7	42.2
0.81	34.65	3.6	5.1	6.3	28.8	56.0
0.9	19.6	1.7	3.9	4.7	59.0	55.4

Table (iv cont.) Sediment Size Analysis Sieving Results - Cores SWF, SWG, SWH, SWJ

Sediment Size Analysis (Sieving) Southwick						
		Differential % coarser than seive size				
Depth (m)	Sample weight (g)	500μm	250μm	125μm	63μm	pan
CORE SWK						
0.01	25.72	3.6	5.9	5.8	29.5	54.9
0.03	39.81	3.8	5.4	5.6	33.9	50.7
0.05	32.38	3.3	5.0	5.2	27.5	58.8
0.08	26.48	1.5	3.6	4.2	31.4	58.8
0.1	28.72	2.8	4.6	5.1	35.1	51.7
0.12	27.26	8.0	10.9	9.7	38.4	55.0
0.14	23.32	3.0	6.1	6.9	38.5	44.9
0.16	33.55	2.5	4.7	4.9	33.9	53.2
0.18	31.96	3.8	6.6	7.2	32.8	49.3
0.21	21.53	3.4	6.9	7.5	28.3	53.2
0.23	26.61	3.5	8.6	8.2	25.0	53.1
0.25	37.58	1.7	2.8	6.1	39.4	46.8
0.27	34.08	1.7	4.8	5.4	40.3	47.4
0.29	28.63	1.0	4.5	6.5	41.0	46.6
0.32	25.45	1.1	3.1	4.1	34.7	56.7
0.34	38.76	1.3	4.2	5.3	34.6	54.4
0.36	27.92	0.8	3.9	5.2	36.5	53.4
0.38	42.42	2.5	6.9	6.7	33.3	50.0
0.4	24.7	1.0	4.6	6.2	41.3	46.6
0.42	35.16	4.4	6.8	6.3	35.8	46.3
0.45	29.19	1.2	3.4	3.6	39.7	51.7
0.47	29.89	1.1	3.3	3.9	44.5	46.5
0.49	34.23	0.9	2.6	3.2	50.4	42.4
0.51	32.98	0.8	2.4	3.0	44.7	48.7
0.53	32.34	0.5	1.7	2.6	50.4	44.6

Table (iv cont.) Sediment Size Analysis Sieving Results - Cores SWK

Sediment Size Analysis (Coulter 230LS) Southwick							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt % < 63 μm	Medium Silt % < 32 μm	Fine Silt % < 16 μm	Very Fine Silt % < 7.8 μm	Clay % < 3.9 μm
CORE SWA							
0.01	52.2	25.5	66.21	19.24	12.59	9.36	6.89
0.27	54.22	25.2	65.12	16.13	10.01	7.21	5.06
0.53	49.46	25.3	71	22.84	13.46	9.13	5.95
0.79	58.65	23.1	57.99	10.46	6.09	4.52	3.41
CORE SWB							
0.01	47.47	25.3	74.16	24.97	15.18	10.34	6.98
0.25	46.67	24.4	74.09	25.49	16.04	10.75	6.56
0.37	58.76	23.5	57.03	11.51	6.45	4.26	2.86
0.49	49.87	26.5	68.96	23.37	15.33	10.7	7.21
0.54	49.03	26.1	70.01	25.71	14.58	8.98	5.56
0.61	55.2	25.7	60.94	17.6	10.38	6.54	4.04
0.73	51.24	25.4	68.71	19.91	12.41	8.92	5.99
0.96	54.9	24.9	63.04	15.77	10.2	6.96	3.98
CORE SWC							
0.01	50.64	25.7	68.89	21.48	13.54	9.53	6.67
0.03	44.47	25.4	75.19	30.76	20	12.62	7.1
0.06	47.92	25.6	72.92	25.04	15.37	10.42	7
0.08	45.9	24.5	74.64	27.67	17.05	10.33	5.68
0.1	46.68	24	74.37	25.66	15.52	9.63	5.31
0.13	43.1	24.5	78.11	31.94	19.66	12.3	6.94
0.15	55.12	24.1	63.11	15.09	9.2	5.95	3.42
0.17	48.15	26	72.27	25.38	15.53	10.23	6.63
0.19	44.25	24.6	76.77	30.12	18.62	11.49	6.4
0.22	41.05	26	80.16	36.4	23.08	14.66	8.56
0.24	53.67	24.4	65.04	16.93	10.21	6.89	4.28
0.26	42.66	24.5	78.79	32.45	20.01	12.58	7.18
0.28	49.86	25.6	69.77	23.06	14.28	8.78	4.69
0.31	49.71	25.7	70.25	22.58	14.06	9.84	6.92
0.33	51.08	25.6	68.38	20.74	13.32	9.03	5.45
0.35	49.55	25.4	68.13	24.58	14.78	8.92	4.81
0.47	49.68	26.2	69.9	23.09	14.68	10.36	7.19
0.58	42.96	25.1	76.99	34.39	20.35	11.63	5.81
0.69	51.18	24.4	69.4	19.42	11.29	7.85	5.4
0.81	56.27	24.1	61.2	14.15	7.75	5.05	3.31
0.92	49.82	25.2	70.5	21.77	13.3	9.56	6.81
CORE SWD							
0.01	51.13	24.7	69.31	19.85	11.6	7.97	5.6
0.24	54.53	24.7	63.63	16.86	9.95	5.46	3.04
0.48	51.39	24.9	68.78	19.78	11.39	7.98	5.69
CORE SWE							
0.01	56.11	25	61.17	14.7	9.26	6.78	4.88
0.25	51.04	25.9	69.35	20.58	12.67	8.94	6.31
0.49	47.41	24.7	72.43	25.47	15.61	10.08	6.34
0.73	49.27	25.8	71.28	23.25	13.8	9.64	6.75
0.85	48.57	26.5	70.79	25.89	15.39	10.06	6.39
0.96	53.62	24.2	65.73	16.45	9.51	6.81	5.05

Table (v) Sediment size analysis Coulter 230LS results
Cores SWA, SWB, SWC, SWD, SWE

Sediment Size Analysis (Coulter 230LS) Southwick							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt % < 63 μm	Medium Silt % < 32 μm	Fine Silt % < 16 μm	Very Fine Silt % < 7.8 μm	Clay % < 3.9 μm
CORE SWF							
0.01	52.69	25.6	67.68	18.28	10.71	7.36	5.1
0.25	48.67	27.2	71.89	25.16	15.29	10.62	7.41
0.36	44.46	25.4	74.74	32.26	19.4	11.29	5.75
0.48	45.69	24.4	75.37	27.2	16.55	10.91	6.8
0.6	47.92	25	71.54	25.85	15.11	9.06	4.89
0.84	47.09	25.4	71.79	28.01	16.76	9.71	4.96
0.95	46.54	26.6	74.46	27.33	17.11	12.36	8.86
CORE SWG							
0.01	45	24.5	75.89	28.6	17.69	11.45	6.95
0.12	41.32	25.2	79.08	37.52	21.83	12.05	5.78
0.23	39.94	24.9	81.28	36.87	23.61	16.32	10.32
0.34	42.74	24.2	78.84	32.92	19.19	11.28	5.82
0.46	39.36	24.7	82.22	37.3	24.11	16.59	10.79
0.57	43.64	25	76.58	32.83	19.39	11.1	5.6
0.68	50.43	25	69.36	20.87	12.96	9.42	6.58
0.79	36.55	23.6	85.19	44.93	25.89	14.19	6.78
0.9	43.09	24.6	78.22	31.16	19.53	13.39	8.85
CORE SWH							
0.01	47.73	26.7	72.14	26.58	16.88	11.47	7.7
0.13	52.59	25.9	64.82	20.73	12.15	7.53	4.5
0.24	46.96	24.6	73.42	26.33	15.57	9.49	5.31
0.48	40.8	26.4	80.64	36.76	23.23	15.31	9.4
0.59	44.93	25.1	75.22	30.76	17.95	10.36	5.22
0.64	41.1	25.6	78.65	38.52	22.97	12.77	6.08
0.71	46.94	24.4	73.48	25.43	16.8	9.91	4.79
0.83	49.24	26	69.71	24.9	14.9	9.16	5.46
0.94	43.91	25	76.56	31.02	20.25	12.24	5.88
CORE SWJ							
0.01	42.96	26.7	77.74	34.51	21.44	12.56	6.56
0.13	45.55	25.9	73.22	30.86	18.9	11.05	5.56
0.35	38.37	24.9	82.71	42.2	25.02	14.28	6.98
0.47	42.83	24.3	79.14	31.26	19.21	12.85	8.07
0.58	47.35	25.9	71.08	28.08	17.12	10.15	5.27
0.69	38.46	26	82.87	40.84	25.8	16.98	10.58
0.81	39.18	25.2	80.78	41.09	25.65	14.59	7.03
0.9	48.42	26.6	71.35	25.42	15.66	11.16	8.05
CORE SWK							
0.01	42.48	25.2	77.93	33.49	21.35	13.79	8.39
0.05	45.58	25.1	74.61	29.18	17.76	10.4	5.46
0.1	45.24	24	76.42	27.94	16.11	9.93	5.89
0.14	41.55	25.4	78.61	35.91	22.21	13.84	8.37
0.18	40.12	44.9	83.96	42.58	26.46	16.82	10.38
0.21	45.3	25.4	74.44	29.51	18.19	11.42	7.12
0.27	40.93	25.9	81.48	35.94	21.9	14.08	8.44
0.32	44.01	25.6	77.51	30.91	18.92	11.89	6.88
0.36	40.95	24.2	81.24	34.88	20.88	13.31	8.02
0.4	37.67	26.2	83.41	42.92	27.2	17.16	10.15
0.45	45.36	24.7	75.21	28.7	17.04	10.83	6.62
0.49	48.34	26.4	71.51	25.29	16.09	11.14	7.58
0.53	47.49	24.5	72.54	25.12	15.4	9.98	6.05

Table (v, cont.) Sediment size analysis Coulter 230LS results
Cores SWF, SWG, SWH, SWJ, SWK

APPENDIX 2

ORCHARDTON RESULTS

Plate	Position on Marsh	September '95	June '96	August '97	Net accretion/erosion		**Accretion rate**
		Average depth(mm)	Average depth (mm)	Average depth (mm)	9 months (mm)	23 months (mm)	**(cm y^{-1})**
1	Mudflat	53	94	147	40	94	**4.9**
2	Mudflat	31	n/f	n/f	*	*	*
3	Pioneer marsh - *Salicornia*	60	58	29	-2	-30	**-1.6**
4	Mudflat	76	n/f	221	*	145	**7.6**
5	Pioneer marsh - *Salicornia*	65	54	41	-11	-24	**-1.3**
6	Pioneer marsh - *Salicornia*	53	66	74	13	21	**1.1**
7	Mudflat - nr. small channel	80	160	199	80	119	**6.2**
8	Mudflat - nr. small rill	54	119	210	65	156	**8.1**
9	Pioneer marsh - *Spartina*	61	90	140	29	79	**4.1**
10	Mudflat	67	n/f	n/f	*	*	*
11	*Spartina* marsh - cliff edge	96	90	97	-6	1	**0.04**
12	Pioneer marsh - *Spartina*	113	121	160	8	47	**2.5**
13	Mudflat	59	102	n/f	42	*	**5.6**
14a	*Spartina* marsh - hummock	97	95	112	-1	16	**0.8**
14b	*Spartina* marsh - hummock	90	87	103	-4	13	**0.7**
15	*Spartina* marsh	90	89	97	-1	7	**0.3**
16	*Spartina* marsh - hummock	107	103	124	-4	18	**0.9**
17	*Sparina* marsh	151	136	137	-15	-14	**-0.7**
18	*Spartina* marsh - hummock	117	110	111	-7	-6	**-0.3**
19	*Spartina* marsh - hummock	114	111	110	-4	-4	**-0.2**
20	*Spartina* marsh - nr. creek	111	115	106	3	-6	**-0.3**
21	*Spartina* marsh - nr. creek	102	106	89	4	-13	**-0.7**
22	*Spartina* marsh - hummock	184	176	188	-7	4	**0.2**
23	*Sparina* marsh	120	128	130	8	10	**0.5**
24	High marsh	135	136	n/f	1	*	**0.2**
25	*Spartina* marsh - nr. creek	138	131	139	-7	2	**0.1**
26	*Sparina* marsh	131	137	140	5	9	**0.4**
27	High marsh - nr. small channel	124	128	n/f	4	*	**0.5**
28	High marsh - nr. creek	97	102	98	5	2	**0.1**
29	High marsh - nr. creek	53	n/f	n/f	*	*	*
30	*Spartina* marsh	98	89	104	-9	7	**0.4**
31	High marsh	103	103	115	1	12	**0.6**

n/f = plate not found
* = unable to calculate

Table (i) Orchardton sedimentation plate results

Loss on Ignition Orchardton					
ORA		ORB		ORC	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	2.61	0.01	2.40	0.01	2.79
0.04	3.00	0.03	2.62	0.04	2.79
0.06	3.59	0.06	2.41	0.06	2.58
0.08	2.81	0.08	3.01	0.08	3.57
0.11	3.01	0.10	2.60	0.11	2.39
0.13	2.20	0.13	2.39	0.13	3.21
0.16	2.59	0.15	2.00	0.16	2.79
0.18	2.82	0.17	2.18	0.18	2.99
0.20	2.81	0.20	2.20	0.20	2.79
0.23	3.01	0.22	2.40	0.23	3.39
0.25	2.39	0.24	1.99	0.25	3.81
0.28	1.81	0.26	1.99	0.28	3.01
0.30	2.00	0.29	1.80	0.30	3.01
0.33	2.61	0.31	1.80	0.33	3.78
0.35	2.59	0.33	1.98	0.35	2.59
0.37	2.22	0.36	2.41	0.37	2.78
0.40	2.20	0.38	2.40	0.40	2.98
0.42	1.80	0.40	1.99	0.42	2.98
0.45	2.58	0.43	2.40	0.45	2.79
0.47	2.40	0.45	2.20	0.47	2.77
0.49	2.00	0.47	2.19	0.49	2.79
0.52	2.40	0.49	1.98	0.52	3.19
0.54	2.00	0.52	2.60	0.54	2.79
0.57	2.00	0.54	3.01	0.57	2.59
0.59	2.21	0.56	3.97	0.59	1.98
0.61	2.20	0.59	3.23	0.61	2.59
0.64	2.19	0.61	2.00	0.64	2.78
0.66	1.78	0.63	1.80	0.66	6.64
0.69	1.39	0.66	2.79	0.69	2.19
0.71	1.20	0.68	3.60	0.71	1.79
0.73	1.80	0.70	3.01	0.73	2.00
0.76	2.20	0.72	2.39	0.76	2.79
0.78	1.80	0.75	1.99	0.78	2.81
0.81	1.99	0.77	2.19	0.81	2.60
0.83	1.39	0.79	2.40	0.83	2.01
0.86	2.39	0.82	2.38	0.86	1.79
0.88	2.79	0.84	2.20	0.88	2.39
0.90	2.59	0.86	2.20	0.90	2.79
0.93	2.40	0.89	2.21	0.93	2.79
0.95	3.39	0.91	3.02	0.95	2.61
0.98	3.62	0.93	4.62	0.98	2.40
		0.95	3.01		
		0.98	3.38		

Table (ii) Loss on ignition results - Cores ORA, ORB, ORC

Loss on Ignition Orchardton					
ORD		ORE		ORF	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	3.18	0.01	3.80	0.01	4.21
0.04	3.58	0.04	3.92	0.04	5.00
0.06	3.40	0.06	3.94	0.06	4.59
0.08	3.39	0.08	3.95	0.08	4.36
0.11	3.36	0.11	3.52	0.11	4.20
0.13	3.01	0.13	3.37	0.13	4.00
0.15	3.39	0.15	3.56	0.15	4.02
0.18	3.39	0.18	1.33	0.18	4.20
0.20	3.19	0.20	3.94	0.20	4.40
0.23	3.20	0.23	3.73	0.23	4.22
0.25	2.80	0.25	3.35	0.25	3.59
0.27	2.59	0.27	3.16	0.27	3.57
0.30	3.01	0.30	3.98	0.30	4.61
0.32	3.19	0.32	3.98	0.32	4.39
0.35	2.98	0.35	4.58	0.35	4.39
0.37	3.19	0.37	3.78	0.37	4.59
0.39	2.80	0.39	3.18	0.39	4.38
0.42	2.81	0.42	2.96	0.42	3.78
0.44	2.78	0.44	2.40	0.44	3.39
0.46	2.79	0.46	3.78	0.46	3.56
0.49	2.58	0.49	3.20	0.49	3.58
0.51	2.99	0.51	3.56	0.51	2.99
0.54	2.61	0.54	2.97	0.54	2.61
0.56	1.99	0.56	2.77	0.56	2.39
0.58	2.80	0.58	3.37	0.58	2.58
0.61	3.58	0.61	3.79	0.61	2.39
0.63	3.18	0.63	3.19	0.63	2.81
0.65	2.61	0.65	3.37	0.65	3.17
0.68	3.19	0.68	2.98	0.68	2.59
0.70	2.60	0.70	2.59	0.70	1.80
0.73	3.19	0.73	2.59	0.73	2.19
0.75	2.58	0.75	3.04	0.75	2.60
0.77	3.39	0.77	2.79	0.77	2.60
0.80	3.18	0.80	3.41	0.80	2.38
0.82	2.79	0.82	3.40	0.82	1.79
0.85	3.19	0.85	2.78	0.85	1.79
0.87	3.61	0.87	2.85	0.87	2.56
0.89	3.40	0.89	2.39	0.89	2.79
0.92	2.81	0.92	2.81	0.92	2.49
0.94	2.79	0.94	3.21	0.94	2.39
0.96	2.81	0.96	3.80	0.96	2.60
0.99	3.80	0.99	3.81	0.99	2.59
0.99	3.21			1.00	3.68

Table (ii, cont.) Loss on ignition results - Cores ORD, ORE, ORF

Loss on Ignition Orchardton					
ORG		ORH		ORJ	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	4.15	0.01	4.99	0.01	2.58
0.03	4.73	0.04	6.16	0.04	3.18
0.06	4.75	0.06	6.26	0.07	4.74
0.08	4.55	0.09	6.18	0.10	3.28
0.10	4.18	0.11	7.09	0.13	6.11
0.13	3.90	0.14	5.00	0.16	5.60
0.15	3.79	0.16	7.20	0.19	5.56
0.17	4.16	0.19	5.75	0.22	6.09
0.20	4.13	0.21	5.98	0.25	6.60
0.22	4.22	0.23	6.25	0.28	4.18
0.24	4.36	0.26	7.23	0.30	5.50
0.27	4.37	0.28	5.68	0.33	6.71
0.29	4.49	0.31	5.00	0.36	6.27
0.31	4.59	0.33	6.01	0.39	5.74
0.34	5.58	0.36	6.75	0.42	5.27
0.36	5.74	0.38	6.46	0.45	4.40
0.38	4.76	0.41	6.31	0.48	4.41
0.41	4.96	0.43	5.57	0.51	4.37
0.43	4.57	0.46	5.15	0.54	5.56
0.45	4.39	0.48	5.16	0.57	5.98
0.48	5.56	0.51	5.34	0.59	9.29
0.50	5.77	0.53	5.53	0.62	4.98
0.52	4.62	0.56	4.49	0.65	4.96
0.55	3.99	0.58	4.15	0.68	4.57
0.57	4.17	0.60	3.56	0.71	5.56
0.59	4.18	0.63	4.58	0.74	4.17
0.62	4.13	0.65	4.80	0.77	3.45
0.64	4.35	0.68	4.94	0.80	2.94
0.66	4.17	0.70	4.29	0.83	2.20
0.69	7.40	0.73	3.38	0.86	2.55
0.71	3.39	0.75	3.17	0.88	2.54
0.73	4.00	0.78	4.80	0.91	2.78
0.76	3.38	0.80	4.13	0.94	2.81
0.78	3.76	0.83	4.79	0.97	2.39
0.80	3.58	0.85	4.95	0.78	4.21
0.83	2.99	0.88	5.00	0.81	3.33
0.85	4.56	0.90	5.13	0.83	2.70
0.87	4.93	0.93	3.80	0.85	2.30
0.90	3.96	0.95	4.93	0.88	2.23
0.92	3.16	0.98	5.38	0.90	2.49
0.94	2.95	1.00	5.85	0.92	1.49
0.97	2.39	0.97	2.55	0.94	1.51
0.99	2.76	0.99	2.97	0.97	1.87
0.97	2.58			0.99	1.89
0.99	2.55				

Table (ii, cont.) Loss on ignition results - Cores ORG, ORH, ORJ

Loss on Ignition Orchardton	
ORK	
Sample (m)	Loss on ignition (%)
0.01	5.00
0.04	4.98
0.06	4.84
0.09	6.00
0.11	5.01
0.14	4.35
0.16	3.99
0.19	5.37
0.21	6.25
0.24	5.01
0.26	4.15
0.29	4.80
0.31	6.47
0.34	6.11
0.36	6.13
0.39	5.53
0.41	5.38
0.44	5.18
0.46	5.59
0.49	5.75
0.51	5.95
0.54	5.73
0.56	5.29
0.59	4.79
0.61	5.94
0.64	5.61
0.66	4.37
0.69	5.57
0.71	5.34
0.74	5.04
0.76	4.73
0.79	4.37
0.81	4.09
0.84	4.96
0.86	4.19
0.89	4.38
0.91	4.22
0.94	4.31
0.96	4.18
0.99	4.95
0.88	1.72
0.90	1.15
0.92	1.55
0.95	1.80
0.97	1.57
0.99	1.29

Table (ii, cont.) Loss on ignition results - Core ORK

Radionuclide Specific Activities and Activity Ratios Core ORA						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	158	3	258	3	0.6
0.05	0.06	205	5	309	6	0.7
0.09	0.11	213	3	291	3	0.7
0.13	0.16	151	4	227	4	0.7
0.17	0.20	191	3	261	4	0.7
0.21	0.25	184	5	242	5	0.8
0.25	0.30	159	3	197	3	0.8
0.29	0.35	220	5	266	6	0.8
0.33	0.40	197	3	225	3	0.9
0.37	0.45	234	6	265	6	0.9
0.41	0.49	151	5	181	6	0.8
0.45	0.54	203	3	214	3	1.0
0.49	0.59	162	6	299	7	0.5
0.53	0.64	227	3	276	4	0.8
0.57	0.69	161	3	186	3	0.9
0.61	0.73	179	4	208	4	0.9
0.65	0.78	122	3	165	3	0.7
0.69	0.83	172	6	192	6	0.9
0.73	0.88	168	5	187	5	0.9
0.77	0.93	125	2	144	2	0.9
0.815	0.98	125	3	162	3	0.8

Table (iii) Radionuclide Specific Activities and Activity Ratios - Core ORA

Radionuclide Specific Activities and Activity Ratios Core ORB						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.01	0.01	191	4	197	3	1.0
0.05	0.06	252	7	238	7	1.1
0.09	0.10	325	4	275	3	1.2
0.13	0.15	271	7	228	5	1.2
0.17	0.20	319	5	224	4	1.4
0.21	0.24	302	8	199	6	1.5
0.25	0.29	404	6	220	4	1.8
0.29	0.33	382	9	268	7	1.4
0.33	0.38	614	7	267	3	2.3
0.37	0.43	705	14	308	8	2.3
0.41	0.47	687	16	266	9	2.6
0.45	0.52	914	12	308	5	3.0
0.49	0.56	1017	21	363	10	2.8
0.53	0.61	732	12	273	6	2.7
0.57	0.66	791	9	378	5	2.1
0.61	0.70	1022	18	441	9	2.3
0.65	0.75	858	19	267	9	3.2
0.69	0.79	720	10	230	4	3.1
0.73	0.84	610	11	214	6	2.9
0.77	0.89	791	11	325	5	2.4
0.81	0.93	1136	14	517	7	2.2
0.86	0.99	882	11	330	5	2.7

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core ORB

Radionuclide Specific Activities and Activity Ratios Core ORC						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity ($Bq\ kg^{-1}$)	^{137}Cs Error ($Bq\ kg^{-1}$)	^{241}Am Specific Activity ($Bq\ kg^{-1}$)	^{241}Am Error ($Bq\ kg^{-1}$)	$^{137}Cs/^{241}Am$ Activity Ratio
0.01	0.01	152	5	155	5	1.0
0.05	0.06	162	2	192	2	0.8
0.09	0.11	106	3	114	2	0.9
0.13	0.16	167	5	163	5	1.0
0.17	0.20	181	4	195	4	0.9
0.21	0.25	224	6	249	6	0.9
0.25	0.30	228	4	192	3	1.2
0.29	0.35	157	5	180	5	0.9
0.33	0.40	177	4	193	4	0.9
0.37	0.45	148	6	133	5	1.1
0.41	0.49	206	3	209	3	1.0
0.45	0.54	157	6	161	5	1.0
0.49	0.59	138	3	138	3	1.0
0.53	0.64	189	7	191	6	1.0
0.57	0.69	203	4	179	3	1.1
0.61	0.73	239	10	206	8	1.2
0.65	0.78	367	11	295	9	1.2
0.69	0.83	576	8	434	6	1.3
0.73	0.88	870	12	872	11	1.0
0.77	0.93	764	17	657	13	1.2
0.81	0.98	478	11	634	13	0.8

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core ORC

Radionuclide Specific Activities and Activity Ratios Core ORD						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	205	5	261	6	0.8
0.05	0.06	191	7	264	7	0.7
0.09	0.11	209	2	268	3	0.8
0.13	0.15	168	3	265	3	0.6
0.17	0.20	200	5	251	6	0.8
0.21	0.25	184	6	251	6	0.7
0.25	0.30	193	3	251	4	0.8
0.29	0.35	200	6	261	7	0.8
0.33	0.39	211	3	240	4	0.9
0.37	0.44	216	5	275	5	0.8
0.41	0.49	177	2	213	2	0.8
0.45	0.54	245	7	257	7	1.0
0.49	0.58	254	8	265	7	1.0
0.53	0.63	236	5	269	5	0.9
0.57	0.68	307	4	360	5	0.9
0.61	0.73	297	8	339	8	0.9
0.65	0.77	341	5	358	5	1.0
0.69	0.82	277	6	208	5	1.3
0.73	0.87	449	6	370	5	1.2
0.77	0.92	355	10	288	8	1.2
0.81	0.96	329	8	226	6	1.5

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core ORD

Radionuclide Specific Activities and Activity Ratios Core ORE						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	248	7	326	8	0.8
0.05	0.06	248	8	307	8	0.8
0.09	0.11	266	8	338	8	0.8
0.13	0.15	305	4	351	4	0.9
0.17	0.20	368	11	397	10	0.9
0.21	0.25	397	8	330	7	1.2
0.25	0.30	727	8	422	5	1.7
0.29	0.35	869	15	447	9	1.9
0.33	0.39	532	12	283	8	1.9
0.37	0.44	104	2	12	1.5	8.8
0.41	0.49	22	2.1	BDL	BDL	NA
0.45	0.54	7	0.9	BDL	BDL	NA
0.49	0.58	7	2.9	BDL	BDL	NA

Radionuclide Specific Activities and Activity Ratios Core ORF						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.01	0.01	309	10	314	9	1.0
0.05	0.06	530	8	347	5	1.5
0.09	0.11	833	24	394	13	2.1
0.13	0.15	1433	24	622	12	2.3
0.17	0.20	1735	20	679	8	2.6
0.21	0.25	1466	26	572	13	2.6
0.25	0.30	1361	28	1388	24	1.0
0.29	0.35	560	15	537	12	1.0
0.33	0.39	249	7	338	8	0.7
0.37	0.44	109	3	93	3	1.2
0.41	0.49	46	6	BDL	BDL	NA
0.45	0.54	19	3	BDL	BDL	NA
0.49	0.58	BDL	BDL	BDL	BDL	NA

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Cores ORE, ORF

Radionuclide Specific Activities and Activity Ratios Core ORG						
Mean Sample	Mean adjusted	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$
Depth (m)	Depth (m)	Specific Activity (Bq/Kg^{-1})	Error (Bq/Kg^{-1})	Specific Activity (Bq/Kg^{-1})	Error (Bq/kg^{-1})	Activity Ratio
0.01	0.01	244	4	294	4	0.8
0.05	0.06	450	10	444	9	1.0
0.09	0.10	509	12	352	9	1.4
0.13	0.15	1033	19	471	11	2.2
0.17	0.20	1124	13	464	6	2.4
0.21	0.24	1504	28	654	16	2.3
0.25	0.29	925	25	794	21	1.2
0.29	0.34	421	9	356	8	1.2
0.33	0.38	123	3	122	2	1.0
0.37	0.43	77	3.6	47	3.3	1.6
0.41	0.48	97	4.8	15	3.5	6.3
0.45	0.52	47	1.8	5	1.7	8.6
0.49	0.57	21	1.8	BDL	BDL	NA
0.53	0.62	1	0.5	BDL	BDL	NA
0.57	0.66	4	1.6	BDL	BDL	NA

Radionuclide Specific Activities and Activity Ratios Core ORH						
Mean Sample	Mean adjusted	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$
Depth (m)	Depth (m)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Activity Ratio
0.01	0.01	341	6	386	6	0.9
0.05	0.06	446	13	496	12	0.9
0.09	0.11	804	21	781	17	1.0
0.13	0.16	855	20	534	13	1.6
0.17	0.21	1596	37	685	19	2.3
0.21	0.26	2150	25	1021	12	2.1
0.25	0.31	975	21	1341	22	0.7
0.29	0.36	424	14	423	11	1.0
0.33	0.41	150	4	144	3	1.0
0.37	0.46	58	3.9	194	39	0.3
0.41	0.51	51	5.4	BDL	BDL	NA
0.45	0.56	17	1.9	BDL	BDL	NA
0.49	0.60	12	2.9	BDL	BDL	NA

Table (iii, cont.) Radionuclide Specific Activities and ActivityRatios - Cores ORG, ORH

Radionuclide Specific Activities and Activity Activity Ratios Core ORJ						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.01	0.01	132	6	135	6	1.0
0.05	0.07	257	8	311	8	0.8
0.09	0.13	373	5	416	5	0.9
0.13	0.19	419	10	462	10	0.9
0.17	0.25	550	13	605	12	0.9
0.21	0.30	534	13	505	11	1.1
0.25	0.36	717	9	709	8	1.0
0.29	0.42	719	10	499	7	1.4
0.33	0.48	956	12	518	6	1.8
0.37	0.54	1495	22	617	11	2.4
0.41	0.59	1438	23	679	13	2.1
0.45	0.65	1310	22	666	13	2.0
0.49	0.71	1279	20	763	13	1.7
0.53	0.77	215	3	115	1	1.9
0.57	0.83	30	3.2	BDL	BDL	NA
0.61	0.88	7	2.6	BDL	BDL	NA
0.65	0.94	2	1.5	BDL	BDL	NA
0.675	0.98	11	1.2	6	1.3	1.7

Radionuclide Specific Activities and Activity Ratios Core ORK						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.01	0.01	369	12	440	11	0.8
0.05	0.06	402	12	419	11	1.0
0.09	0.11	761	10	552	7	1.4
0.13	0.16	881	19	478	12	1.8
0.17	0.21	1648	30	780	16	2.1
0.21	0.26	1448	37	670	20	2.2
0.25	0.31	2323	48	971	24	2.4
0.29	0.36	1452	18	1626	19	0.9
0.33	0.41	598	17	501	6	1.2
0.37	0.46	315	10	375	9	0.8
0.41	0.51	138	2	127	2	1.1
0.45	0.56	70	4.6	25	3.7	2.9
0.49	0.61	48	2.5	5	1.8	9.3
0.53	0.66	24	3.8	BDL	BDL	NA

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Cores ORJ, ORK

CORE ORA						
Depth (cm)		Differental % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	31.01	1.9	4.3	4.0	26.2	64.0
21(25)	32	3.0	5.6	5.2	18.0	68.4
41(49)	35.81	0.6	1.9	3.5	34.9	59.0
61(73)	36.48	0.3	1.2	3.2	19.9	75.2
81.5(98)	53.84	3.3	4.6	6.1	29.8	56.3

CORE ORB						
Depth (cm)		Differential% coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	29.06	3.4	6.1	5.4	17.8	66.9
21(24)	30.8	1.7	3.4	3.8	18.7	72.2
41(47)	32.28	1.8	4.0	4.3	16.8	73.2
61(70)	34.17	2.8	5.3	5.9	14.2	72.4
81(93)	29.45	4.7	7.0	7.3	21.3	59.7

CORE ORC						
Depth (cm)		Differential% coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	22.37	2.0	4.5	4.2	16.3	73.6
21(25)	30.37	3.4	6.3	6.1	21.3	63.1
41(49)	27	2.8	5.2	5.0	18.9	68.4
61(70)	37.77	1.6	3.7	4.6	22.0	68.1
81(98)	30.55	1.0	3.0	4.6	28.7	62.8

CORE ORD						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	43.09	4.3	6.2	4.9	23.4	61.1
41(49)	31.18	1.9	3.1	3.3	14.1	77.5
61(73)	35.4	1.8	4.3	5.0	24.2	64.5

Table (iv) Sediment size analysis Seiving Results - Cores ORA, ORB, ORC, ORD

CORE ORE						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	38.26	2.8	5.9	5.5	17.5	68.3
21(25)	32.83	1.7	4.4	5.1	17.3	71.5
29(35)	28.21	4.2	6.7	5.6	16.9	66.0
41(49)	33.52	2.0	4.8	5.0	21.6	66.6
49(58)	33.55	2.4	4.9	5.1	20.6	66.9

CORE ORF						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	33.67	6.4	8.0	6.9	17.1	61.3
13(15)	29.6	5.2	9.3	9.2	15.4	60.8
21(25)	30.69	3.5	6.5	5.7	18.3	65.4
29(35)	28.84	6.5	9.3	8.1	15.8	60.3
41(49)	33.85	2.3	5.4	5.6	18.6	68.8

CORE ORG						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	20.15	2.4	67.5	7.3	17.0	65.9
9(10)	30.76	2.1	5.8	5.8	15.4	70.8
21(24)	32.08	2.8	6.0	6.2	17.1	68.1
41(48)	30.96	5.0	8.9	7.5	12.4	66.2
61(71)	36.09	2.1	4.5	4.8	16.3	72.2
81(94)	36.8	1.8	4.2	4.3	16.6	73.1

CORE ORH						
Depth (cm)		% coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	27.23	6.1	9.9	8.5	10.4	65.0
9(11)	20.32	5.5	12.6	11.4	11.0	59.0
21(26)	26.69	7.5	9.9	7.6	10.6	64.5
41(51)	37.09	2.1	5.8	5.9	10.7	75.3
61(75)	36.21	3.0	5.7	4.8	10.3	76.0
81(100)	20.37	3.5	8.7	8.6	13.9	64.5

Table (iv cont.) Sediment size analysis Seiving Results - Cores ORE, ORF, ORG, ORH

CORE ORJ						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	22.64	1.7	3.1	2.9	14.4	78.5
21(30)	27.17	4.3	8.2	8.5	11.9	68.0
41(59)	28.44	3.8	6.6	7.5	11.0	71.3
49(71)	27.69	3.5	6.9	8.1	14.2	67.6
61(88)	34.03	3.1	5.7	4.7	14.7	71.3

CORE ORK						
Depth (cm)		Differential % coarser than seive size				
(adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
1(1)	15.72	5.1	8.8	8.5	12.2	66.5
21(26)	27.31	3.3	6.2	5.9	13.3	71.1
25(31)	24.26	6.0	8.9	7.6	10.9	66.3
41(51)	30.49	4.4	6.4	6.3	13.6	69.6
61(88)	35.09	3.4	6.5	5.4	17.7	67.1

Table (iv cont.) Sediment size analysis Seiving Results - Cores ORJ, ORK

Sediment Size Analysis (Coulter 230LS) Orchardton							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt < 6 3μm	Medium Silt < 32 μm	Fine Silt < 16 μm	Very Fine Silt < 7.8 μm	Clay < 3.9 μm
CORE ORA							
0.01	55.3	26	61.15	17.21	10.93	7.04	4.4
0.49	60.85	22.8	53.3	9.05	5.75	3.97	2.65
0.73	59.73	22.9	55.69	9.73	5.83	4.01	2.69
0.98	49.14	26	69.62	25.08	15.59	9.56	5.67
CORE ORB							
0.01	42.31	25.5	77.33	35.82	21.95	12.35	6.01
0.24	52.68	25.2	65.71	19.24	11.48	7.39	4.64
0.47	49.34	25.9	70.29	24.17	14.07	8.9	5.49
0.7	48.6	25.2	72.59	24.34	13.43	8.21	4.95
0.93	45.96	26.2	72.14	30.78	19.4	10.97	5.27
CORE ORC							
0.01	48.91	26.6	69.75	26.12	15.61	9.51	5.71
0.25	46.95	24.8	72.83	27.36	15.88	8.97	4.58
0.49	51.32	25.7	67.18	21.69	12.87	7.95	4.73
0.73	52.15	24.6	67.51	19.12	10.67	6.59	3.97
0.98	57.36	25.8	57.08	15.4	9.96	6.26	3.75
CORE ORD							
0.01	46.55	25.1	72.65	28.05	17.58	10.18	5.18
0.49	55.72	23.5	62.85	13.85	7.68	4.9	3.1
0.73	50.43	26	68.52	22.89	14.18	8.78	5.2
CORE ORE							
0.1	44.38	25.3	75.56	31.8	19.13	10.93	5.47
0.25	48.68	26.4	71.06	25.69	15.25	9.3	5.53
0.35	44.55	25.4	75.07	31.96	19.29	10.67	5.12
0.49	47.88	25.6	70.5	26.79	16.88	9.59	4.72
0.58	47.36	25.2	71.89	26.5	16.81	10	5.13
CORE ORF							
0.01	41.35	25.1	78.93	37.27	22.24	12.06	5.61
0.15	37.95	26	82.92	44.21	26.69	14.36	6.39
0.25	44.51	25.5	74.64	32.22	19.95	10.97	5.16
0.35	39.63	26.1	80.96	40.84	25.31	13.84	6.27
0.49	47.17	25.3	71.89	27.31	17.05	9.88	4.98
CORE ORG							
0.01	40.22	23.5	81.68	37.15	22.38	12.18	5.69
0.1	47.3	25.8	73.56	26.85	15.92	9.54	5.58
0.24	44.62	25.6	74.58	31.85	19.97	11.27	5.41
0.48	40.33	25.7	80.49	38.85	23.97	13.51	6.43
0.7	49.05	25.6	71.1	24.06	14.13	8.9	5.51
0.93	51.39	25	68.12	20.17	11.78	7.78	5.05
CORE ORH							
0.01	33.19	24.3	88.31	52.4	31.55	16.86	7.5
0.11	31.12	25	89.48	57.9	35.63	19.02	8.32
0.26	36.35	26.3	84.29	47.34	29.62	16.25	7.26
0.51	41.94	26	79.33	35.66	21.84	12.69	6.28
0.73	40.2	24.8	82.68	37.01	21.67	12.95	6.81
0.96	35.92	26.4	84.29	48.16	30.76	17.36	7.97

Table (v) Sediment size analysis Coulter 230LS results
Cores ORA, ORB, ORC, ORD, ORE, ORF, ORG, ORH

Sediment Size Analysis (Coulter 230LS) Orchardton							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt % < 63 μm	Medium Silt % < 32 μm	Fine Silt % < 16 μm	Very Fine Silt % < 7.8 μm	Clay % < 3.9 μm
CORE ORJ							
0.01	56.18	25.1	61.77	14.64	8.3	5.32	3.39
0.3	38.77	27.6	83.63	43.09	24.42	13.26	6.32
0.59	36.43	25.7	86.99	46.44	24.84	13.5	6.56
0.71	38.83	26.7	83.31	42.56	24.21	13.26	6.35
0.88	47.01	24.8	72.9	26.7	15.94	9.56	5.2
CORE ORK							
0.01	36.21	23.1	86.34	45.1	25.06	13.51	6.37
0.26	43.72	24.7	77.37	31.86	18.48	10.73	5.51
0.31	38.97	27.3	82.12	42.86	26.11	14.65	6.87
0.51	41.15	24.6	79.82	36.9	21.47	11.99	5.81
0.88	43.85	25	76.2	32.33	19.65	11.32	5.77

Table (v, cont.) Sediment size analysis Coulter 230LS results
Cores ORJ, ORK

APPENDIX 3

CAERLAVEROCK RESULTS

Plate	Position on Marsh	October '95 Average depth (mm)	June '96 Average depth (mm)	August '97 Average depth (mm)	Net accretion/erosion 9 months (mm)	Net accretion/erosion 14 months (mm)	Net accretion/erosion 23 months (mm)	**Accretion rate ($cm\ y^{-1}$)**
1	High marsh	82	98	113	16	15	30	**1.6**
2	High marsh - pan edge	104	118	154	14	36	50	**2.6**
3	High marsh - pan edge	75	98	121	23	23	45	**2.4**
4	High marsh	106	113	149	7	36	43	**2.2**
5	High marsh	135	150	192	15	42	58	**3.0**
6	Pioneer marsh at pan edge - *Puccinellia*	84	112	157	28	45	73	**3.8**
8	High marsh	85	98	137	13	39	52	**2.7**
9	Marsh edge	131	7	eroded	-124	*	*	**-16.5**
9a	Marsh edge - stripped turf	~	124	94	~	-29	*	**-2.5**
10	Marsh edge	106	eroded		*	*	*	*
10a	Marsh edge	~	117	eroded	~	*	*	*
11	Marsh edge	135	eroded		*	*	*	*
11a	Creek edge	~	125	eroded	~	*	*	*
12	Creek edge - stripped turf	106	93	85	-13	-8	-21	**-1.1**
13	Creek edge	101	eroded		*	*	*	*
13a	Marsh edge - stripped turf	~	116	85	~	-31	*	**-2.6**
14	High marsh	118	113	137	-4	24	20	**1.0**
15	Marsh edge - stripped turf	113	52	eroded	-60	*	*	**-8.0**
15a	Marsh edge - stripped turf	~	106	61	~	-45	*	**-3.8**
16	Marsh edge - stripped turf	122	eroded		*	*	*	*
16a	Marsh edge - stripped turf	~	140	105	~	-35	*	**-3.0**
17	Mudflat	124	201	n/f	77	*	*	**10.2**
18	Pioneer marsh - *Puccinellia*	50	n/f	n/f	*	*	*	*
19	Mudflat	88	162	n/f	74	*	*	**9.8**

n/f = not found
* = unable to calculate
~ = data not available

Table (i) Caerlaverock (eroding site) sedimentation plate results

Loss on Ignition Caerlaverock (eroding site)					
CLA		CLB		CLC	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	3.17	0.01	5.62	0.01	2.60
0.03	2.39	0.04	6.24	0.03	2.79
0.06	2.20	0.06	5.63	0.05	3.20
0.08	2.40	0.08	5.42	0.07	3.59
0.10	2.81	0.11	5.82	0.10	3.60
0.12	2.40	0.13	2.99	0.12	2.60
0.15	1.60	0.15	3.61	0.14	2.00
0.17	1.61	0.18	3.59	0.16	2.39
0.19	2.39	0.20	3.41	0.18	2.20
0.21	1.29	0.22	4.23	0.20	2.20
0.24	1.98	0.25	4.22	0.22	2.20
0.26	1.60	0.27	2.99	0.24	2.59
0.28	1.80	0.29	2.99	0.27	1.80
0.30	1.20	0.32	2.60	0.29	2.40
0.33	2.19	0.34	1.59	0.31	2.59
0.35	2.40	0.36	2.39	0.33	2.20
0.37	1.61	0.39	2.20	0.35	2.20
0.39	1.80	0.41	1.60	0.37	1.40
0.42	2.20	0.44	1.80	0.39	1.79
0.44	2.19	0.46	1.79	0.41	1.40
0.46	2.00	0.48	2.20	0.44	1.59
0.48	2.00	0.51	1.80	0.46	2.00
0.51	2.20	0.53	2.20	0.48	4.02
0.53	2.19	0.55	2.39	0.50	4.80
0.55	1.80	0.58	2.40	0.52	5.20
0.57	1.80	0.60	1.60	0.54	3.59
0.60	3.19	0.62	1.99	0.56	3.61
0.62	3.98	0.65	1.99	0.59	4.22
0.64	3.80	0.67	2.00	0.61	3.39
0.66	3.61	0.69	1.59	0.63	3.40
0.69	2.38	0.72	1.40	0.65	3.62
0.71	3.21	0.74	1.60	0.67	3.21
0.73	2.60	0.76	2.00	0.69	3.59
0.75	2.59	0.79	2.20	0.71	3.80
0.78	2.20	0.81	2.79	0.73	2.79
0.80	2.00	0.84	2.00	0.76	2.79
0.82	1.39	0.86	1.39	0.78	1.40
0.84	1.19	0.88	1.99	0.80	1.80
0.87	2.00	0.91	2.19	0.82	1.99
0.89	2.40	0.93	2.20	0.84	1.60
0.91	2.78	0.95	2.20	0.86	1.80
0.93	2.38	0.98	4.02	0.88	1.59
0.96	1.60			0.90	1.79
0.98	1.59			0.93	1.20
				0.95	1.80
				0.97	2.00
				0.99	2.00

Table (ii) Loss on ignition results - Cores CLA, CLB, CLC

Loss on Ignition Caerlaverock (eroding site)					
CLD		CLE		CLF	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	4.59	0.01	3.79	0.01	3.98
0.03	3.18	0.03	4.00	0.03	3.39
0.05	4.21	0.05	3.98	0.05	2.58
0.07	3.60	0.08	4.23	0.07	3.40
0.09	3.61	0.10	4.39	0.10	3.39
0.12	4.01	0.12	3.82	0.12	2.40
0.14	3.82	0.14	3.60	0.14	2.40
0.16	3.79	0.16	2.20	0.16	1.60
0.18	3.60	0.18	3.73	0.18	1.59
0.20	2.40	0.21	3.19	0.20	1.60
0.22	4.01	0.23	7.03	0.22	1.20
0.24	2.41	0.25	13.71	0.24	1.58
0.26	3.21	0.27	8.38	0.27	1.39
0.28	3.00	0.29	7.43	0.29	1.39
0.31	3.39	0.32	6.87	0.31	2.00
0.33	2.81	0.34	5.19	0.33	3.47
0.35	1.60	0.36	4.62	0.35	2.21
0.37	1.80	0.38	5.59	0.37	1.20
0.39	1.39	0.40	6.22	0.39	3.83
0.41	1.79	0.42	3.99	0.41	5.48
0.43	3.01	0.45	3.79	0.44	8.08
0.45	1.79	0.47	2.78	0.46	3.80
0.47	4.61	0.49	3.01	0.48	3.61
0.49	9.29	0.51	2.60	0.50	4.79
0.52	7.82	0.53	1.39	0.52	3.61
0.54	8.05	0.55	2.76	0.54	3.21
0.56	6.64	0.58	2.19	0.56	4.20
0.58	6.01	0.60	1.79	0.59	3.60
0.60	6.25	0.62	2.19	0.61	4.40
0.62	4.65	0.64	1.61	0.63	3.59
0.64	4.21	0.66	1.19	0.65	2.20
0.66	3.19	0.68	1.40	0.67	2.20
0.68	2.99	0.71	1.79	0.69	2.39
0.71	2.20	0.73	1.80	0.71	1.79
0.73	1.80	0.75	1.40	0.73	2.00
0.75	2.00	0.77	1.99	0.76	2.19
0.77	1.20	0.79	1.00	0.78	1.60
0.79	1.99	0.82	0.80	0.80	1.80
0.81	1.79	0.84	2.79	0.82	1.79
0.83	1.79	0.86	2.40	0.84	1.40
0.85	1.40	0.88	2.20	0.86	1.40
0.87	1.60	0.90	2.58	0.88	1.40
0.89	1.80	0.92	1.20	0.90	1.70
0.92	1.80	0.95	0.80	0.93	2.60
0.94	1.39	0.97	1.20	0.95	2.79
0.96	1.80	0.99	2.59	0.97	2.40
0.98	2.19			0.99	2.59

Table (ii, cont.) Loss on ignition results - Cores CLD, CLE, CLF

Loss on Ignition Caerlaverock (eroding site)					
CLG		CLH		CLJ	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	4.18	0.01	4.40	0.01	2.40
0.03	4.18	0.03	1.80	0.03	3.81
0.05	2.79	0.05	2.99	0.05	3.20
0.08	2.60	0.07	2.80	0.08	4.00
0.10	2.79	0.09	3.18	0.10	2.40
0.12	3.19	0.12	2.81	0.12	1.60
0.14	2.98	0.14	2.59	0.14	1.99
0.16	2.38	0.16	2.21	0.16	4.83
0.19	2.79	0.18	3.21	0.18	3.99
0.21	3.41	0.20	4.17	0.20	1.81
0.23	4.18	0.22	2.80	0.23	2.79
0.25	3.59	0.24	2.79	0.25	1.40
0.27	3.20	0.26	2.61	0.27	1.40
0.30	2.40	0.28	2.00	0.29	1.60
0.32	2.00	0.31	1.60	0.31	2.19
0.34	2.40	0.33	2.40	0.33	1.61
0.36	3.39	0.35	2.79	0.35	1.60
0.38	2.80	0.37	3.01	0.38	1.80
0.41	4.18	0.39	4.02	0.40	2.00
0.43	7.46	0.41	7.06	0.42	1.60
0.45	6.84	0.43	6.02	0.44	3.81
0.47	6.24	0.45	5.42	0.46	2.80
0.49	2.79	0.47	5.02	0.48	6.05
0.52	7.60	0.49	4.23	0.51	5.86
0.54	4.21	0.52	4.83	0.53	4.43
0.56	4.63	0.54	3.00	0.55	3.81
0.58	5.03	0.56	4.42	0.57	4.23
0.60	4.83	0.58	5.20	0.59	3.82
0.63	5.00	0.60	4.00	0.61	3.43
0.65	3.61	0.62	4.39	0.63	4.62
0.67	3.99	0.64	3.39	0.66	4.01
0.69	2.99	0.66	4.00	0.68	3.41
0.71	2.40	0.68	2.20	0.70	2.20
0.74	2.99	0.71	2.99	0.72	2.40
0.76	2.79	0.73	2.58	0.74	1.80
0.78	2.98	0.75	3.20	0.76	1.40
0.80	2.78	0.77	2.98	0.78	2.00
0.82	2.20	0.79	2.79	0.81	2.40
0.85	1.40	0.81	2.58	0.83	2.20
0.87	2.58	0.83	2.40	0.85	2.39
0.89	3.18	0.85	2.98	0.87	1.39
0.91	3.19	0.87	2.99	0.89	1.00
0.93	3.20	0.89	2.99	0.91	1.80
0.96	2.61	0.92	2.99	0.94	1.99
0.98	2.40	0.94	2.60	0.96	2.40
		0.96	2.79	0.98	3.20
		0.98	3.79		

Table (ii, cont.) Loss on ignition results - Cores CLG, CLH, CLJ

Loss on Ignition Caerlaverock (eroding site)	
CLK	
Sample (m)	Loss on ignition (%)
0.01	4.19
0.03	3.03
0.06	4.00
0.08	3.01
0.10	2.81
0.13	4.21
0.15	2.20
0.17	3.65
0.20	3.40
0.22	1.39
0.24	2.01
0.27	2.21
0.29	3.00
0.31	5.81
0.34	9.07
0.36	8.67
0.38	6.22
0.41	6.44
0.43	4.22
0.45	4.41
0.48	4.82
0.50	4.23
0.52	4.02
0.55	4.01
0.57	3.19
0.59	2.21
0.62	1.79
0.64	1.81
0.66	2.20
0.69	2.61
0.71	2.01
0.73	2.00
0.76	1.40
0.78	1.79
0.80	1.20
0.83	1.80
0.85	1.80
0.87	1.80
0.90	1.00
0.92	1.41
0.94	1.79
0.97	2.20
0.99	2.40
0.95	1.80
0.97	1.57
0.99	1.29

Table (ii, cont.) Loss on ignition results - Core CLK

Radionuclide Specific Activities and Activity Ratios
Core CLA

Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity (Bq kg^{-1})	^{137}Cs Error (Bq kg^{-1})	^{241}Am Specific Activity (Bq kg^{-1})	^{241}Am Error (Bq kg^{-1})	$^{137}Cs/^{241}Am$ Activity Ratio
0.02	0.02	116	5	67	5	1.7
0.06	0.07	102	5	65	4	1.6
0.1	0.11	118	3	69	2	1.7
0.14	0.16	82	4	51	3	1.6
0.2	0.22	109	3	61	2	1.8
0.28	0.31	99	5	58	4	1.7
0.36	0.40	114	3	73	2	1.6
0.44	0.49	BDL	BDL	BDL	BDL	NA
0.52	0.58	2	1	BDL	BDL	NA

Radionuclide Specific Activities and Activity Ratios
Core CLB

Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity (Bq kg^{-1})	^{137}Cs Error (Bq kg^{-1})	^{241}Am Specific Activity (Bq kg^{-1})	^{241}Am Error (Bq kg^{-1})	$^{137}Cs/^{241}Am$ Activity Ratio
0.02	0.02	1079	19	341	9	3.2
0.06	0.07	645	12	390	8	1.7
0.1	0.12	155	3	25	2	6.3
0.14	0.16	57	3.0	BDL	BDL	NA
0.2	0.24	15	0.6	BDL	BDL	NA
0.28	0.33	BDL	BDL	BDL	BDL	NA
0.36	0.42	BDL	BDL	BDL	BDL	NA

Radionuclide Specific Activities and Activity Ratios
Core CLC

Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs Specific Activity (Bq/Kg^{-1})	^{137}Cs Error (Bq/Kg^{-1})	^{241}Am Specific Activity (Bq/Kg^{-1})	^{241}Am Error (Bq/kg^{-1})	$^{137}Cs/^{241}Am$ Activity Ratio
0.02	0.02	102	4	53	3	1.9
0.06	0.06	136	3	91	4	1.5
0.1	0.11	145	6	76	5	1.9
0.14	0.15	92	2	39	1	2.4
0.2	0.21	90	4	36	3	2.5
0.28	0.30	106	3	43	2	2.5
0.36	0.38	85	3	62	3	1.4
0.44	0.47	521	12	145	6	3.6
0.52	0.55	271	9	191	8	1.4
0.6	0.64	29	1.7	BDL	BDL	N/A

Table (iii) Radionuclide Specific Activities and Activity Ratios - Cores CLA, CLB, CLC

Radionuclide Specific Activities and Activity Ratios Core CLD						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.02	0.02	134	2	104	2	1.3
0.06	0.06	144	4	94	3	1.5
0.1	0.11	143	3	105	2	1.4
0.14	0.15	127	4	91	4	1.4
0.2	0.21	116	2	72	1	1.6
0.28	0.29	116	2	59	2	2.0
0.36	0.38	66	3	17	2	3.8
0.44	0.46	264	8	147	6	1.8
0.52	0.55	426	11	124	6	3.4
0.6	0.63	41	3	BDL	BDL	N/A
0.68	0.72	10	1	BDL	BDL	N/A

Radionuclide Specific Activities and Activity Ratios Core CLE						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.02	0.02	162	3	116	3	1.4
0.06	0.07	138	5	93	4	1.5
0.1	0.11	145	3	80	3	1.8
0.14	0.15	136	5	66	4	2.1
0.2	0.22	468	7	156	3	3.0
0.28	0.30	385	11	248	8	1.6
0.36	0.39	19	5	BDL	BDL	NA

Table (iii, cont.) Radionuclide Specific Activities and Activity Ratios - Core CLD, CLE

CORE CLA						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	31.71	2.2	2.6	2.9	45.9	46.2
20(22)	30.22	1.2	1.5	2.3	50.4	44.9
44(49)	34.35	2.2	2.8	2.7	41.7	50.1

CORE CLB						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	25.27	12.0	11.7	9.1	30.5	36.5
20(24)	29.77	7.4	6.7	5.5	40.7	39.2

CORE CLC						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	28.45	1.6	2.7	5.0	58.9	31.4
20(21)	30.17	1.2	2.4	2.9	52.6	40.8
44(47)	29.3	4.4	4.1	3.9	50.0	37.2
68(72)	125.27	1.3	1.2	1.0	9.2	7.4

CORE CLD						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	27.79	2.7	2.6	4.4	42.9	47.2
20(21)	29.08	1.8	2.4	3.3	45.1	47.1
44(46)	25.57	6.1	5.0	4.8	48.7	36.3
68(72)	29.73	3.6	3.6	3.6	37.7	51.2

Table (iv) Sediment Size Analysis Seiving Results - Cores CLA, CLB, CLC, CLD

CORE CLE						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	28.67	4.1	4.3	3.8	31.7	55.9
20(22)	20.66	7.6	5.0	4.2	37.8	45.2
44(48)	30.37	1.0	1.2	2.0	56.2	39.5

CORE CLJ						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	24.74	0.5	1.0	2.3	48.4	47.8
44(47)	24.19	5.3	5.7	5.3	44.6	39.0
68(72)	26.95	1.6	2.2	2.3	59.3	35.3

Table (iv, cont.) Sediment Size Analysis Seiving Results - Cores CLE, CLJ

Sediment Size Analysis (Coulter 230LS) Caerlaverock Eroding Site							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt % < 63 μm	Medium Silt % < 32 μm	Fine Silt % < 16 μm	Very Fine Silt % < 7.8 μm	Clay % < 3.9 μm
CORE CLA							
0.02	54.83	23.2	65.3	14.33	6.99	4.46	2.94
0.22	57.71	22.7	61.02	10.69	5.63	3.78	2.61
0.49	52.83	23.8	67.8	17.57	8.67	5.2	3.25
CORE CLB							
0.02	42.01	24	80.17	35.11	18.14	9.53	4.84
0.24	46.67	24.4	74.04	27.46	14.62	8.13	4.46
CORE CLC							
0.02	56.08	24.2	62.47	14.37	7.33	4.44	2.77
0.21	56.94	23	61.41	12.23	6.14	3.96	2.61
0.47	51.74	25.5	67.51	21.52	11.4	6.44	3.75
0.72	46.18	24.9	73.87	29.16	16	8.76	4.5
CORE CLD							
0.02	56.07	23	64.08	12.18	6.2	4.07	2.74
0.21	53.77	23.5	66.77	15.82	7.75	4.84	2.99
0.46	51.8	26	67.35	22.43	11.19	5.91	3.25
0.72	51.92	27.3	64.28	24.14	13.68	7.94	4.7
CORE CLE							
0.02	46.03	23.9	78.12	26.26	12.99	7.76	4.7
0.22	52.05	25.7	67.34	21.38	10.67	5.84	3.32
0.48	60.08	22.4	56.64	8.54	4.63	3.26	2.39

Table (v) Sediment size analysis Coulter 230LS results
Cores CLA, CLB, CLC, CLD, CLE

Plate	Position on marsh	June '96 Average depth (mm)	August '97 Average depth (mm)	September '98 Average depth (mm)	Net accretion/erosion 14 months (mm)	Net accretion/erosion 27 months (mm)	**Accretion rate ($cm\ y^{-1}$)**
1	Low marsh	109	123	143	14	34	**1.5**
2	Low marsh	129	142	171	13	43	**1.9**
3	High marsh	132	n/f	161	*	29	**1.3**
4	High marsh	135	151	164	16	29	**1.3**
5	Low marsh	106	n/f	150	*	45	**2.0**
6	Pan	124	n/f	n/f	*	*	*
7	High marsh	123	n/f	166	*	43	**1.9**
8	Low marsh	122	140	167	18	45	**2.0**
9	Low marsh	103	n/f	156	*	53	**2.3**
10	Pioneer marsh	92	n/f	n/f	*	*	*
11	Pioneer marsh	101	128	158	27	58	**2.6**
12	Pioneer marsh	114	n/f	153	*	39	**1.7**
13	Bare mud	77	n/f	123	*	46	**2.0**
14	Bare mud	95	n/f	140	*	45	**2.0**
15	Mudflat	84	134	174	50	90	**4.0**
16	Mudflat	90	130	128	40	37	**1.7**
17	Mudflat	91	134	163	44	72	**3.2**
18	Pioneer marsh	88	n/f	n/f	*	*	*
19	Pioneer marsh	105	n/f	169	*	64	**2.8**
20	Pioneer marsh	118	n/f	175	*	57	**2.5**
21	Pioneer marsh	100	n/f	158	*	59	**2.6**
22	Bare mud	107	n/f	n/f	*	*	*
23	Pioneer marsh	106	139	169	33	63	**2.8**
24	Pioneer marsh	137	160	186	24	49	**2.2**
25	Bare mud	130	186	212	56	82	**3.7**
26	Mudflat	101	n/f	n/f	*	*	*
27	Mudflat	107	148	180	42	73	**3.3**
28	Mudflat	93	134	175	41	82	**3.7**

n/f = not found
* = unable to calculate

Table (vi) Caerlaverock (accreting site) sedimentation plate results

Loss on Ignition Caerlaverock (accreting site)					
CKA		CKB		CKC	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	2.77	0.01	1.79	0.01	1.80
0.03	2.94	0.03	1.79	0.03	1.80
0.05	3.19	0.06	2.00	0.06	1.99
0.08	2.77	0.08	2.17	0.08	1.70
0.10	2.39	0.10	2.39	0.10	1.80
0.12	1.99	0.12	1.58	0.12	1.99
0.14	1.59	0.14	1.40	0.14	1.60
0.16	1.99	0.17	1.38	0.17	1.98
0.18	2.19	0.19	1.20	0.19	2.19
0.21	1.99	0.21	1.39	0.21	2.01
0.23	1.60	0.23	1.58	0.23	1.39
0.25	1.39	0.26	1.59	0.26	2.40
0.27	1.60	0.28	1.39	0.28	1.19
0.29	1.98	0.30	1.19	0.30	1.00
0.32	2.00	0.32	1.00	0.32	1.59
0.34	2.00	0.34	1.20	0.34	1.59
0.36	1.62	0.37	1.38	0.37	1.00
0.38	1.58	0.39	0.99	0.39	0.99
0.40	2.00	0.41	1.59	0.41	0.99
0.42	1.59	0.43	1.56	0.43	0.99
0.45	2.79	0.46	1.19	0.46	1.40
0.47	2.01	0.48	1.79	0.48	1.59
0.49	1.58	0.50	1.37	0.50	2.00
0.51	1.59	0.52	1.39	0.52	1.20
0.53	1.78	0.54	1.60	0.54	1.60
0.55	1.99	0.57	1.58	0.57	1.40
0.58	1.78	0.59	1.39	0.59	1.20
0.60	1.79	0.61	1.20	0.61	1.39
0.62	1.80	0.63	1.78	0.63	1.40
0.64	1.58	0.66	1.60	0.66	0.98
0.66	1.60	0.68	1.59	0.68	1.40
0.68	1.59	0.70	1.19	0.70	1.59
0.71	1.59	0.72	1.39	0.72	1.39
0.73	1.99	0.74	2.00	0.74	1.40
0.75	1.96	0.77	2.37	0.77	1.39
0.77	1.40	0.79	2.01	0.79	1.61
0.79	1.60	0.81	2.19	0.81	1.60
0.82	1.61	0.83	1.59	0.83	1.59
0.84	1.78	0.86	1.56	0.86	1.78
0.86	1.39	0.88	1.60	0.88	1.79
0.88	1.60	0.90	1.99	0.90	1.19
0.90	1.57	0.92	2.20	0.92	1.19
0.92	1.79	0.94	1.99	0.94	1.41
0.95	1.98	0.97	2.59	0.97	2.57
0.97	2.60	0.99	2.60	0.99	2.80
0.99	3.73				

Table (vii) Loss on ignition results - Cores CKA, CKB, CKC

Loss on Ignition Caerlaverock (accreting site)					
CKD		CKE		CKF	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	2.79	0.01	2.61	0.01	3.62
0.03	2.39	0.04	2.20	0.03	4.41
0.06	1.98	0.06	3.00	0.05	6.59
0.08	2.38	0.08	3.01	0.08	4.65
0.10	2.58	0.11	2.79	0.10	3.41
0.13	2.00	0.13	3.61	0.12	4.02
0.15	2.58	0.15	2.00	0.14	3.21
0.17	2.18	0.18	1.80	0.16	3.20
0.19	1.39	0.20	2.40	0.18	3.00
0.22	1.59	0.23	2.59	0.21	2.62
0.24	1.80	0.25	1.79	0.23	2.42
0.26	1.80	0.27	1.39	0.25	2.00
0.28	1.59	0.30	0.99	0.27	1.99
0.31	1.39	0.32	1.80	0.29	1.80
0.33	1.41	0.35	1.59	0.32	1.59
0.35	1.20	0.37	1.58	0.34	1.00
0.38	1.19	0.39	1.40	0.36	1.20
0.40	1.19	0.42	1.39	0.38	0.80
0.42	1.40	0.44	1.99	0.40	0.99
0.44	1.38	0.46	1.98	0.42	1.20
0.47	1.39	0.49	2.18	0.45	1.00
0.49	1.20	0.51	1.59	0.47	1.20
0.51	1.40	0.54	1.98	0.49	1.00
0.53	1.39	0.56	2.18	0.51	1.00
0.56	1.00	0.58	1.40	0.53	1.00
0.58	1.40	0.61	1.60	0.55	1.00
0.60	1.40	0.63	2.20	0.58	1.39
0.63	1.00	0.65	2.20	0.60	1.40
0.65	1.39	0.68	1.99	0.62	1.20
0.67	1.40	0.70	1.98	0.64	0.80
0.69	2.00	0.73	1.98	0.66	1.59
0.72	1.18	0.75	2.20	0.68	1.80
0.74	1.40	0.77	2.40	0.71	1.20
0.76	1.39	0.80	2.18	0.73	1.20
0.78	1.60	0.82	2.00	0.75	1.81
0.81	1.39	0.85	1.60	0.77	1.59
0.83	1.60	0.87	1.60	0.79	1.40
0.85	1.61	0.89	2.01	0.82	2.00
0.88	1.60	0.92	1.40	0.84	1.60
0.90	1.59	0.94	2.18	0.86	1.60
0.92	1.79	0.96	1.80	0.88	1.80
0.94	1.20	0.99	1.81	0.90	2.79
0.97	1.98			0.92	1.60
				0.95	2.21
				0.97	1.99
				0.99	2.20

Table (vii, cont.) Loss on ignition results - Cores CKD, CKE, CKF

Loss on Ignition Caerlaverock (accreting site)					
CKG		CKH		CKJ	
Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)	Sample (m)	Loss on ignition (%)
0.01	1.98	0.01	2.59	0.01	2.40
0.03	2.40	0.04	2.79	0.03	3.61
0.06	2.00	0.06	2.40	0.06	3.20
0.08	1.99	0.09	2.59	0.08	4.42
0.10	1.99	0.11	1.80	0.10	4.98
0.13	1.78	0.14	2.00	0.12	3.79
0.15	2.20	0.16	2.18	0.14	3.41
0.17	1.98	0.19	1.80	0.17	5.21
0.20	1.60	0.22	2.63	0.19	2.99
0.22	1.59	0.24	2.01	0.21	2.40
0.24	1.39	0.27	1.40	0.23	1.21
0.26	1.19	0.29	1.20	0.26	2.58
0.29	1.20	0.32	1.60	0.28	2.20
0.31	1.59	0.34	1.19	0.30	2.61
0.33	1.39	0.37	2.36	0.32	2.58
0.36	1.39	0.39	1.39	0.34	2.39
0.38	1.59	0.42	1.00	0.37	1.80
0.40	1.20	0.44	1.33	0.39	1.99
0.43	1.20	0.47	1.40	0.41	2.00
0.45	1.60	0.49	1.20	0.43	1.80
0.47	1.79	0.52	1.80	0.46	1.58
0.49	1.79	0.54	1.40	0.48	1.39
0.52	1.40	0.57	1.20	0.50	1.79
0.54	1.58	0.59	1.21	0.52	1.20
0.56	1.39	0.62	1.19	0.54	1.59
0.59	1.59	0.65	1.59	0.57	1.58
0.61	1.79	0.67	1.59	0.59	1.58
0.63	1.79	0.70	1.39	0.61	1.39
0.66	1.99	0.72	0.80	0.63	1.80
0.68	1.40	0.75	1.80	0.66	2.00
0.70	0.99	0.77	1.40	0.68	1.80
0.72	1.79	0.80	1.40	0.70	1.41
0.75	1.60	0.82	1.39	0.72	1.60
0.77	1.79	0.85	0.99	0.74	1.80
0.79	2.01	0.87	1.61	0.77	2.20
0.82	1.78	0.90	2.00	0.79	1.60
0.84	1.40	0.92	1.80	0.81	1.59
0.86	2.18	0.95	1.59	0.83	2.40
0.89	1.59	0.97	1.40	0.86	2.00
0.91	1.60	0.92	2.74	0.88	2.20
0.93	1.39	0.94	2.94	0.90	1.80
0.95	1.79	0.97	2.55	0.92	1.98
0.98	1.79	0.99	2.97	0.94	2.18
0.97	2.58			0.97	2.00
0.99	2.55			0.99	2.00

Table (vii, cont.) Loss on ignition results - Cores CKG, CKH, CKJ

Loss on Ignition Caerlaverock (accreting site)	
CKK	
Sample (m)	Loss on ignition (%)
0.01	2.00
0.03	1.61
0.06	3.43
0.08	2.00
0.10	2.20
0.12	2.21
0.14	1.20
0.17	3.21
0.19	4.02
0.21	2.79
0.23	0.40
0.26	1.81
0.28	1.60
0.30	1.40
0.32	3.81
0.34	3.41
0.37	3.00
0.39	2.00
0.41	1.40
0.43	2.58
0.46	1.99
0.48	1.99
0.50	1.40
0.52	2.40
0.54	1.59
0.57	2.01
0.59	1.39
0.61	1.79
0.63	1.20
0.66	0.79
0.68	1.00
0.70	1.60
0.72	1.40
0.74	1.59
0.77	1.20
0.79	1.40
0.81	2.20
0.83	4.38
0.86	4.00
0.88	2.99
0.90	3.01
0.92	1.20
0.94	3.41
0.97	1.60
0.99	1.40

Table (vii, cont.) Loss on ignition results - Core CKK

Radionuclide Specific Activities and Activity Ratios Core CKA						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.02	0.02	97	2	52	2	1.87
0.06	0.07	97	1	47	1	2.08
0.1	0.11	94	2	44	2	2.14
0.14	0.15	118	3	38	2	3.16
0.2	0.22	223	3	25	1	9.05
0.28	0.30	246	3	30	1	8.28
0.36	0.39	288	9	60	5	4.83
0.44	0.48	97	5	BDL	BDL	N/A
0.52	0.57	12	1	BDL	BDL	N/A

Radionuclide Specific Activities and Activity Ratios Core CKB						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.02	0.02	BDL	BDL	BDL	BDL	NA
0.06	0.07	BDL	BDL	BDL	BDL	NA
0.1	0.11	104	5	53	4	2.0
0.14	0.16	114	6	45	5	2.5
0.2	0.23	176	4	32	2	5.5
0.28	0.32	257	8	36	4	7.1
0.36	0.41	307	10	85	6	3.6
0.44	0.51	109	3	5	2	22
0.52	0.60	17	4	BDL	BDL	N/A

Radionuclide Specific Activities and Activity Ratios Core CKC						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	Specific Activity (Bq kg^{-1})	Error (Bq kg^{-1})	
0.02	0.02	BDL	BDL	BDL	BDL	NA
0.06	0.07	102	2	53	2	1.9
0.1	0.11	128	5	67	4	1.9
0.14	0.16	121	3	57	2	2.1
0.2	0.22	131	6	54	4	2.4
0.28	0.31	181	8	45	5	4.0
0.36	0.40	276	5	39	2	7.1
0.44	0.49	203	17	36	4	5.6
0.52	0.58	22	1	BDL	BDL	N/A

Table (viii) Radionuclide Specific Activities and Activity Ratios - Cores CKA, CKB, CKC

Radionuclide Specific Activities and Activity Ratios Core CKD						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.02	0.02	94	3	48	2	2.0
0.06	0.07	116	6	61	5	1.9
0.1	0.11	136	3	67	3	2.0
0.14	0.16	128	5	60	4	2.2
0.2	0.23	184	4	44	2	4.2
0.28	0.32	259	8	28	4	9.1
0.36	0.41	258	9	25	5	10.5
0.44	0.54	23	9	BDL	BDL	N/A

Radionuclide Specific Activities and Activity Ratios Core CKE						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.02	0.02	126	5	72	4	1.7
0.06	0.07	138	2	87	2	1.6
0.1	0.12	162	5	91	4	1.8
0.14	0.17	126	3	56	2	2.3
0.2	0.24	246	8	56	5	4.4
0.28	0.33	293	9	44	5	6.6
0.36	0.43	329	5	88	3	3.7
0.44	0.52	29	14	BDL	BDL	N/A

Radionuclide Specific Activities and Activity Ratios Core CKF						
Mean Sample Depth (m)	Mean adjusted Depth (m)	^{137}Cs		^{241}Am		$^{137}Cs/^{241}Am$ Activity Ratio
		Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	Specific Activity ($Bq\ kg^{-1}$)	Error ($Bq\ kg^{-1}$)	
0.02	0.02	157	5	106	4	1.5
0.06	0.07	201	3	124	2	1.6
0.1	0.11	368	12	123	6	3.0
0.14	0.15	345	12	71	6	4.9
0.2	0.22	442	13	115	7	3.8
0.28	0.30	261	5	114	3	2.3
0.36	0.39	29	3	19	3	1.5
0.44	0.48	10	3	BDL	BDL	N/A
0.52	0.57	5	2	BDL	BDL	N/A

Table (viii, cont.) Radionuclide Specific Activities and Activity Ratios - Cores CKD, CKE, CKF

CORE CKA						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	28.77	1.4	2.3	4.8	41.5	49.5
20(23)	31.73	0.9	1.0	2.1	74.7	21.6
44(49)	28.53	1.2	1.3	2.2	61.5	33.8

CORE CKB						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	33.41	1.0	1.3	2.3	50.7	45.0
20(23)	28.63	0.3	0.7	1.5	71.2	26.3
3641)	30.23	0.9	1.5	1.8	63.9	32.0
52(60)	22.78	0.7	0.9	1.7	58.5	37.8

CORE CKC						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	29.12	1.2	1.6	2.2	46.3	49.2
36(40)	30.55	0.7	0.8	1.1	71.8	25.7
52(58)	26.9	0.1	0.4	1.0	52.9	45.2

CORE CKD						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	26.12	1.9	1.8	2.1	50.3	43.8
20(23)	27.25	0.9	1.4	1.8	62.9	32.8
36(41)	34.07	0.4	0.6	0.9	64.8	33.2

Table (ix) Sediment Size Analysis Seiving Results - Core CKA, CKB, CKC, CKD

CORE CKE						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	27.18	2.2	2.2	2.3	37.7	55.5
20(24)	32.89	1.5	1.8	2.2	61.6	32.9
52(62)	24.91	0.7	1.0	1.7	48.2	48.3

CORE CKF						
Depth (cm)		% coarser than seive size				
(Adjusted)	Weight of sample(g)	500μm	250μm	125μm	63μm	pan
2(2)	25.46	4.4	3.6	3.9	32.7	55.3
20(22)	25.16	2.9	3.4	3.4	43.9	46.1
44(48)	27.14	1.3	1.7	1.7	56.4	39.1

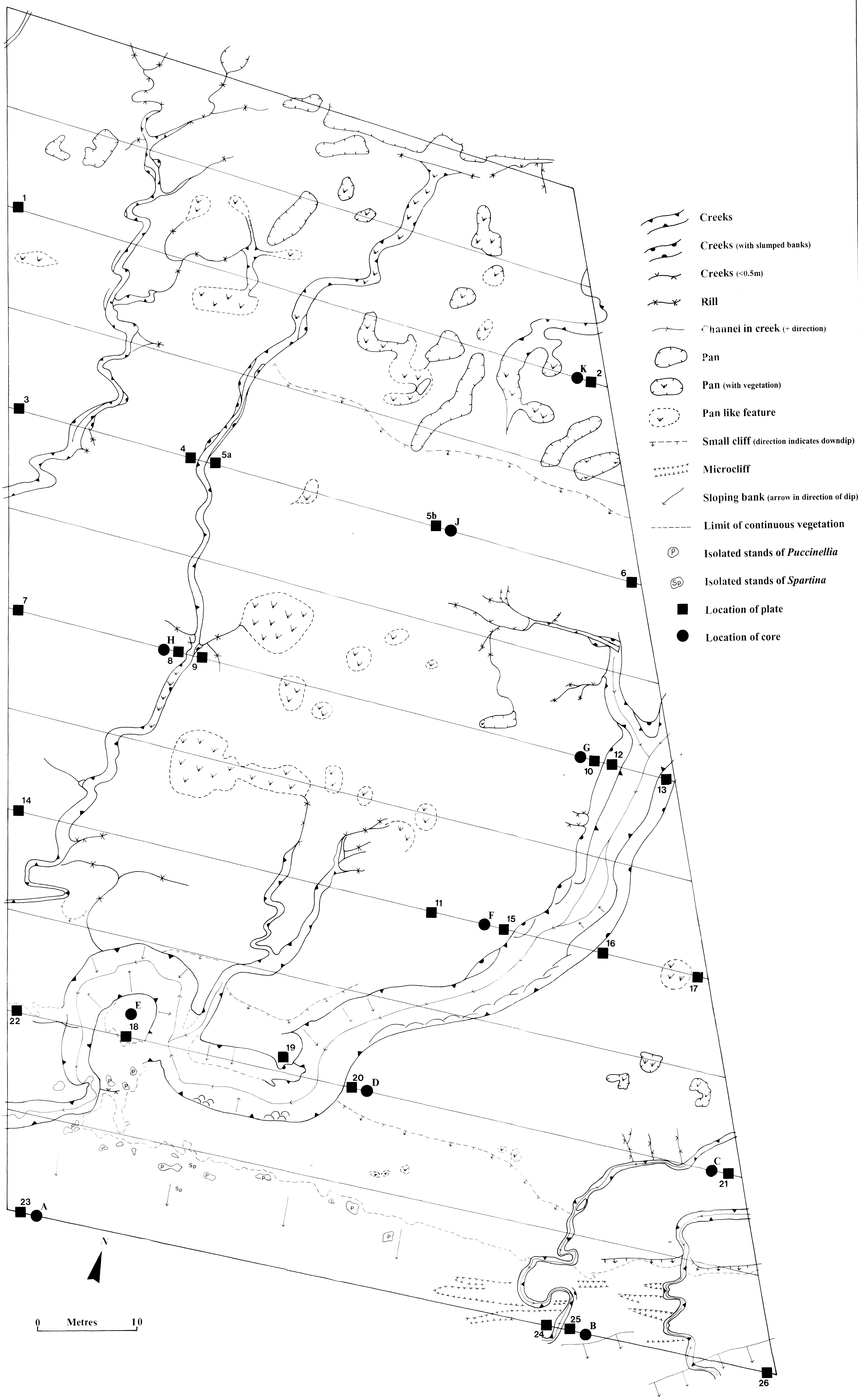
Table (ix, cont.) Sediment Size Analysis Seiving Results - Core CKE, CKF

Sediment Size Analysis (Coulter 230LS) Caerlaverock Accreting Site							
Depth (m)	Mean (μm)	Std. Dev. (μm)	Coarse Silt % < 63 μm	Medium Silt % < 32 μm	Fine Silt % < 16 μm	Very Fine Silt % < 7.8 μm	Clay % < 3.9 μm
CORE CKA							
0.02	60.1	22	56.36	8.37	4.23	3.08	2.35
0.23	61.4	22.3	52.23	8.49	4.98	3.51	2.57
0.49	60.77	21.3	55.41	7.07	4.08	3.08	2.41
CORE CKB							
0.02	63.27	21.6	49.88	6.23	3.37	2.54	2.06
0.23	60.92	22.2	54.29	8.25	4.63	3.24	2.39
0.41	60.1	22.9	54.75	9.83	5.84	4.02	2.78
0.6	60.97	21.9	54.79	7.55	4.4	3.24	2.47
CORE CKC							
0.02	58.33	21.9	59.81	9.51	5.01	3.47	2.5
0.4	60.42	22.6	54.45	9.28	5.35	3.7	2.64
0.58	61.8	21.7	53.26	6.8	3.91	2.95	2.32
CORE CKD							
0.02	56.67	22.7	62.87	11.7	5.89	3.82	2.62
0.23	57.51	24	59.23	13.39	6.89	4.14	2.62
0.41	59.81	21.5	56.99	8.23	4.27	3.07	2.36
CORE CKE							
0.02	54.62	23.3	65.6	14.68	7.36	4.51	2.9
0.24	55.46	23.4	63.56	14.42	6.98	4.21	2.7
0.62	60.07	21.9	56.53	8.12	4.43	3.19	2.39
CORE CKF							
0.02	52.6	24.1	69.48	17.24	8.43	4.98	3.09
0.22	52.95	24.1	67.02	18.04	9.03	5.28	3.27
0.48	56.87	24.1	60.4	13.66	7.72	4.99	3.25

Table (x) Sediment size analysis Coulter 230LS results
Cores CKA, CKB, CKC, CKD, CKE, CKF

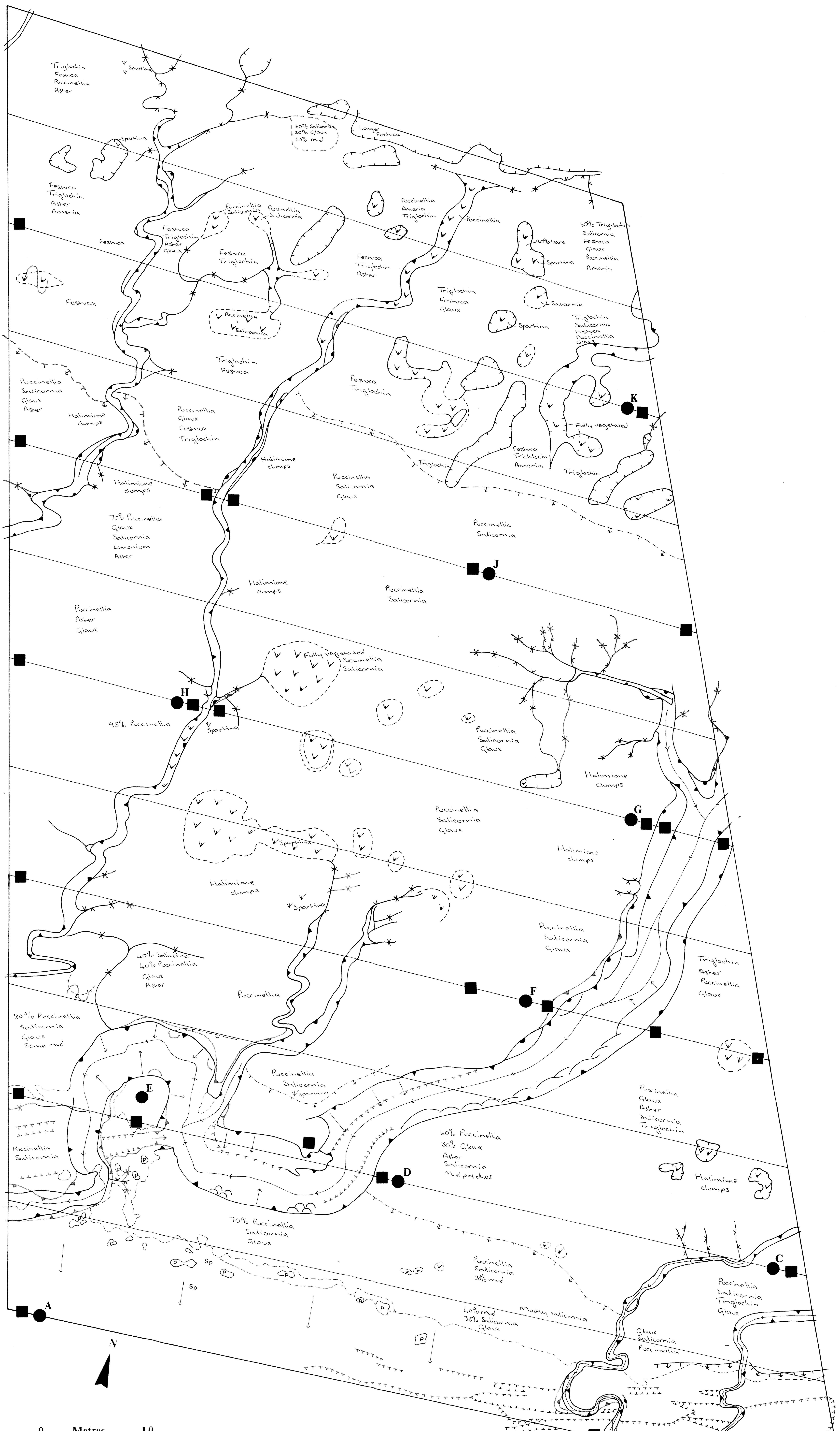
Southwick Merse – Map 1a

Geomorphology



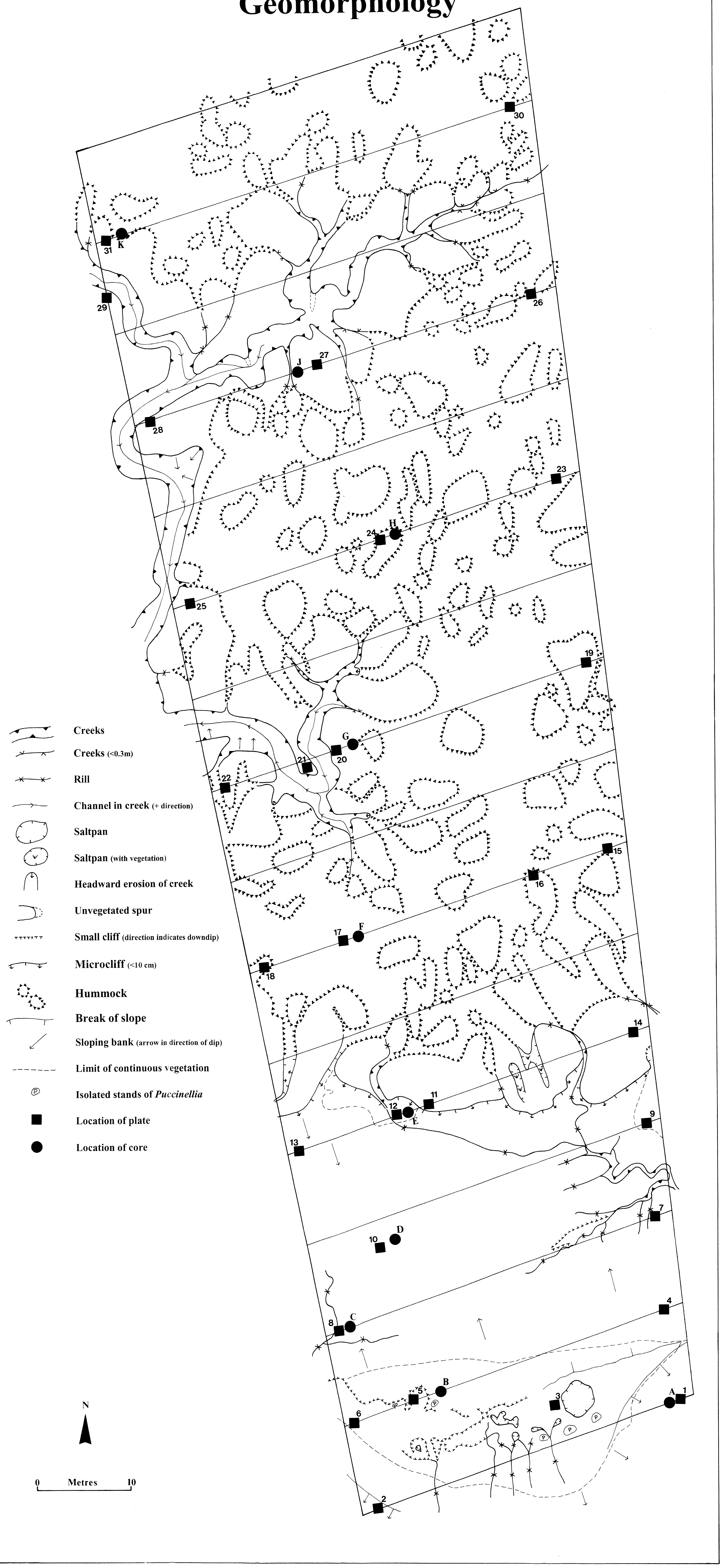
Southwick Merse – Map 1b

Vegetation and recent changes



Orchardton Merse – Map 2a

Geomorphology



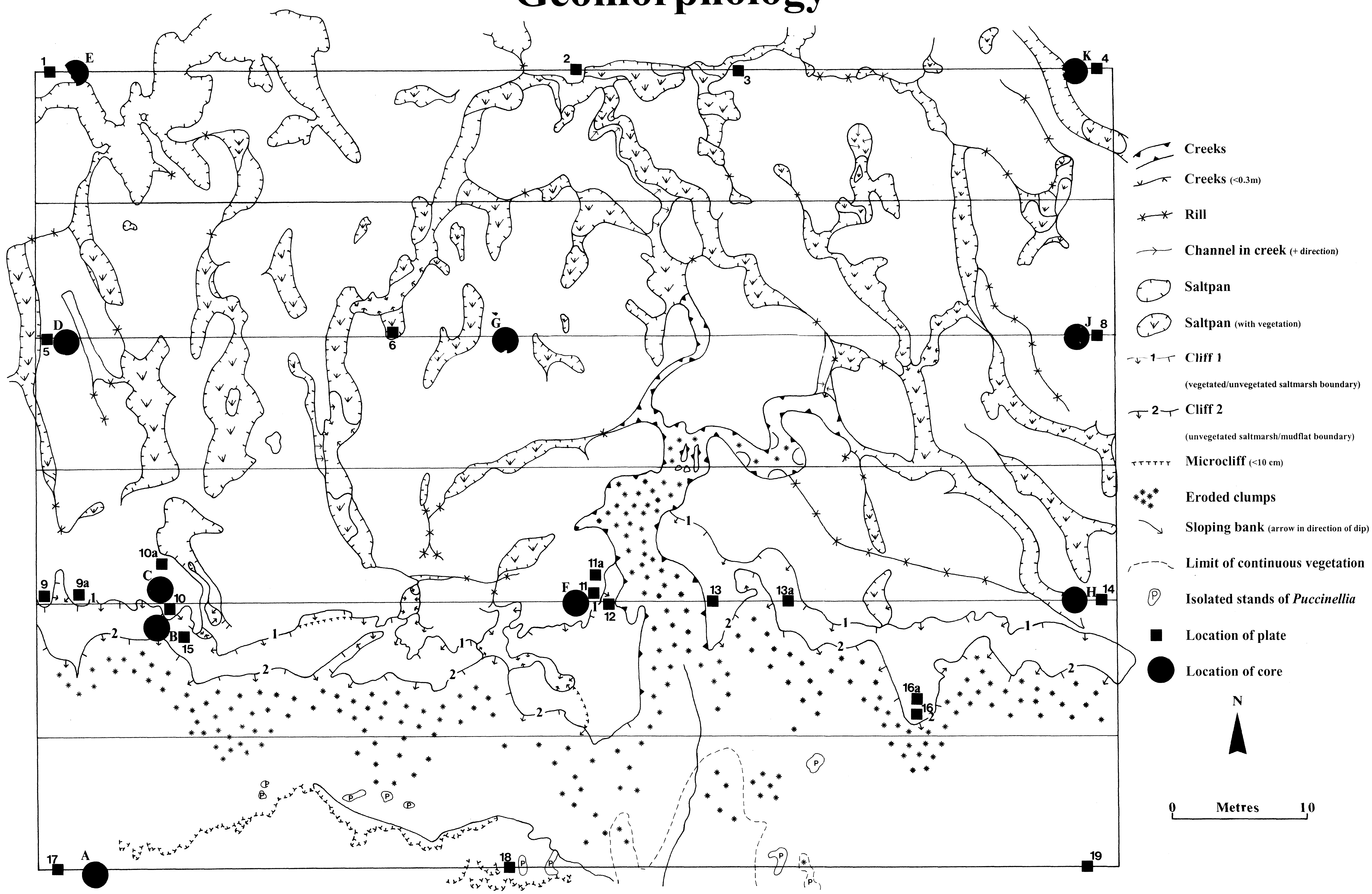
Orchardton merse – Map 2b

Vegetation and recent changes

Caerlaverock Merse – Map 3a

(Eroding site)

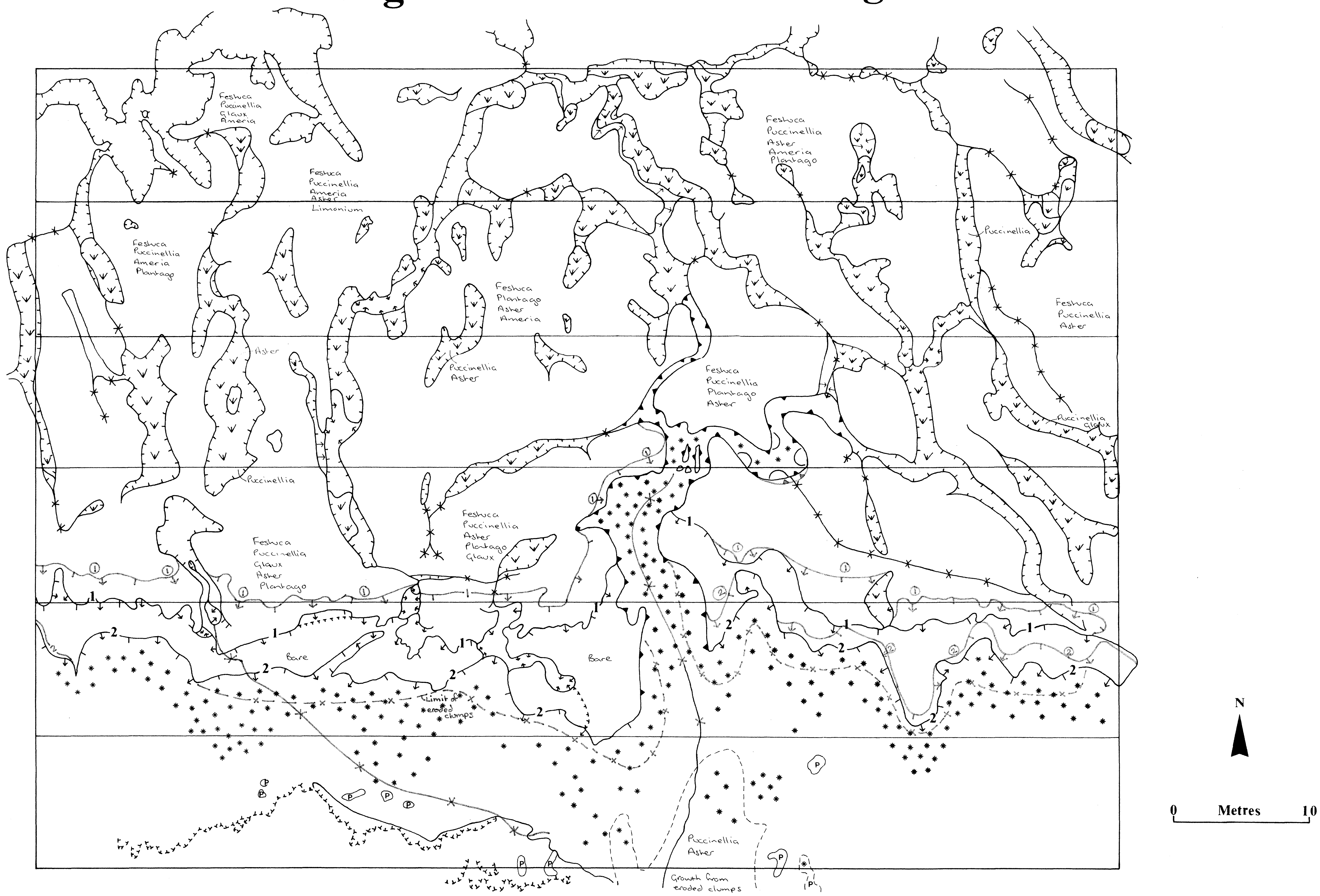
Geomorphology



Caerlaverock Merse – Map 3b

(Eroding site)

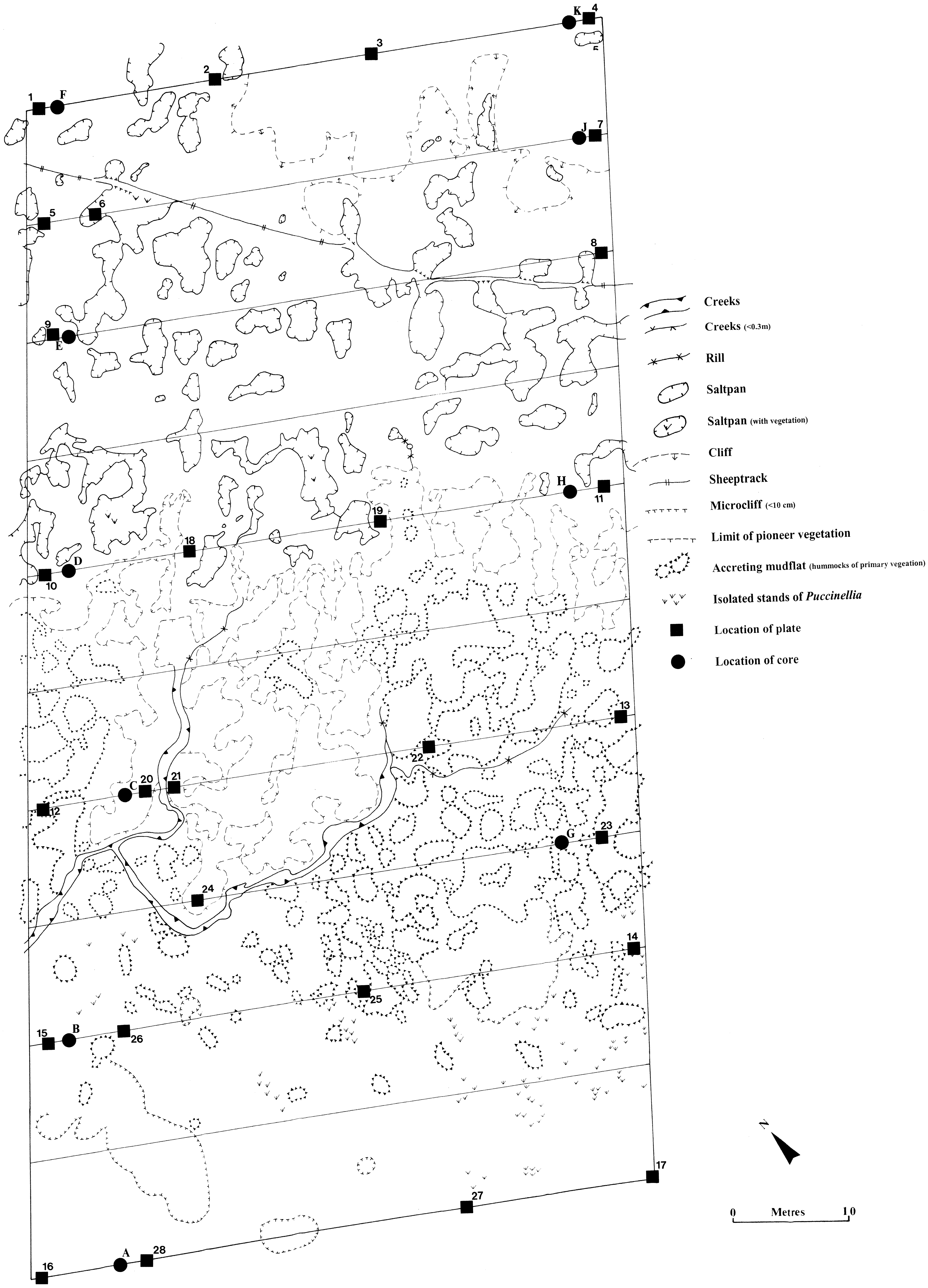
Vegetation and recent changes



Caerlaverock Merse – Map 3c

(Accreting site)

Geomorphology



Caerlaverock Merse – Map 3d

(Accreting site)

Vegetation and recent changes